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PROCEEDINGS OF THE SOCIETY OF ARTS.

THIRTY-SECOND YEAR, 1893-94.

THURSDAY, November 9, 1893.

THE 450th meeting of the SOCIETY OF ARTS was held at the Institute this day at 8 P.M., Professor W. T. Sedgwick in the chair.

The records of the previous meeting were read and approved. Messrs. Herbert H. Barnes, James L. McQuarrie, and George S. Moynahan, of Boston, Charles M. March, of Portland, and J. Foster White, of Brookline, were duly elected Associate Members of the Society.

The following paper was read by title:

"Origin of Parallel and Intersecting Joints," by Prof. W. O. Crosby.

The Chairman then introduced Mr. George W. Fuller, Biologist in charge Lawrence Experiment Station, who read a paper on "The Removal of Pathogenic Bacteria from Drinking Water by Sand Filtration." The paper is printed in full in the present number of the *Quarterly*. It was followed by discussion on the part of the Chairman and others, and the meeting then adjourned.

THURSDAY, November 23, 1893.

The 451st meeting of the SOCIETY OF ARTS was held at the Institute this day at 8 P.M., Dr. D. R. Dewey in the chair.

The records of the previous meeting were read and approved. Messrs. Charles H. Alden, Jr., Charles C. Blake, Robert D. Evans, Joseph H. Goodspeed, W. B. Hardy, George H. Hood, G. Russell Lincoln, John A. Pray, and Walter I. Towne, all of Boston, were duly elected Associate Members of the Society.

The following papers were read by title:

"Determination of the Electrolytic Dissociation of Salts in Solubility Experiments," by A. A. Noyes, Ph.D.

"On Wurtz's Method for the Differentiation of Bacillus Typhi Abdominalis from Bacillus Coli Communis, and its Application to the Examination of Contaminated Drinking Water," by Albert P. Mathews, S.B.

The Chairman then introduced Hon. Frank P. Bennett, of Everett, who read a paper on "The Endowment Craze in Massachusetts." After a long discussion of the subject and of related topics, the Chairman extended the thanks of the Society to Mr. Bennett, and declared the meeting adjourned.

THURSDAY, December 14, 1893.

The 452d meeting of the SOCIETY OF ARTS was held at the Institute this day at 8 P.M., President Walker in the chair.

The records of the previous meeting were read and approved. Messrs. Francis Harrington, William H. Goodwin, Jr., Alfred H. Sawyer, E. N. Foss, and Henry P. Curtis, all of Boston, were duly elected Associate Members of the Society.

The following papers were read by title:

"Note on Normal Intestinal Bacilli of the Horse and of Certain Other Domesticated Animals," by Harrison G. Dyar and Simeon C. Keith, Jr.

"Preliminary Note on a Method for the Harmonic Analysis of Alternating Currents," by Frank A. Laws, S.B.

The President then introduced Mr. Howard A. Carson, Chief Engineer of the Metropolitan Sewerage Commission, who read a paper on "The Metropolitan Sewerage System of Massachusetts." The paper was very fully illustrated with the lantern, and is printed in the present number of the *Quarterly*. At its close the President extended the thanks of the Society to Mr. Carson, and declared the meeting adjourned.

CLEMENT W. ANDREWS, *Secretary.*

SOME RECENT PHOTOGRAPHIC INVESTIGATIONS OF THE SUN.

By GEORGE E. HALE, S.B.

Read October 25, 1893.

PHOTOGRAPHY has long occupied an important position among the methods of solar research. To it we owe the valuable record of the spotted condition of the sun's surface preserved at Greenwich; accurate representations of the corona obtained at total eclipses since 1860; the beautiful maps of the solar spectrum of Rowland and Higgs; and, to name no others, a score of such additions to our knowledge. In very recent times it has been applied to the study of the spectra and forms of the chromosphere, prominences, spots, and faculæ. It is the purpose of the present paper to describe briefly some of the methods and results of these more recent investigations.

THE ULTRA-VIOLET SPECTRUM OF THE CHROMOSPHERE AND PROMINENCES.

The advantages offered by photography for exploring the invisible region of the ultra-violet were early recognized, and spectroscopists were not slow to avail themselves of this means of recording the more refrangible portions of solar and metallic spectra. It was not until the spring of 1891, however, that the first photograph of the ultra-violet prominence spectrum taken apart from a total eclipse was obtained at the Kenwood Observatory. In these early photographs the principal thing that strikes the attention is the great intensity of the bright H and K lines. It was found that these lines were always present in prominences, where they were not only much brighter than the hydrogen lines, but seemed to attain even greater elevations above the limb. Careful wave-length determinations showed the bright H and K lines of the prominences to agree in position with the two strong lines of the calcium spectrum in this region, and there can thus be

little doubt that the calcium plays a most important part in solar phenomena. By comparing in intensity and length the H line of calcium and the slightly less refrangible line of hydrogen in a photograph taken with radial slit, it will be seen that calcium sometimes ascends to even greater elevations than hydrogen. For this reason Professor Young has doubted whether the heavy molecules of calcium may not be converted into some light form by the intense heat of the sun.

The distorted forms of the H and K lines, indicating motion in the line of sight, are photographed with great ease, and accurate determinations of velocity can be made by measuring the negatives. In such work the sensitive plate has great advantages over the eye, for the changes in form of the distorted lines are frequently too rapid to admit of accurate visual measurement.

The first photographs of the chromosphere and prominence spectrum were taken with a telescope having a 12-inch *visual* objective, and consequently but a small portion of the more refrangible region of the spectrum was in focus on a single plate. In addition to the H and K lines and the hydrogen line near H, the two hydrogen lines α and β[1] of the stellar series were obtained. Subsequently a 12-inch *photographic* objective made it possible to obtain photographs in which seventy-four ultra-violet lines are shown. Among them are the entire series of hydrogen lines occurring as dark lines in the ultra-violet spectra of the white stars. In addition to the magnesium triplet at λ 3830 and a number of iron lines, there are many lines as yet unidentified.

Thanks to the aid of photography, the ultra-violet spectrum of the chromosphere and prominences is now as well known as the visible spectrum.

CHROMOSPHERE AND PROMINENCE FORMS.

Prior to the work at the Kenwood Observatory but one photograph of the form of a prominence had been taken without a total eclipse. In 1870 Professor Young used the H line for this purpose, the image of a prominence through a widely open slit being received on a wet collodion plate. The result was so unsatisfactory that the experiment was not repeated.

[1] In the nomenclature for the hydrogen series proposed by Vogel and Huggins, the lines referred to are designated ζ and η.

The discovery of the extreme brightness of the H and K lines in prominences, together with the breadth of the dark bands in which they lie, seemed to offer new encouragement for work in this direction, and fairly good photographs of prominence forms were made at the Kenwood Observatory through an open slit by the aid of these lines. The completion of the spectroheliograph in January, 1892, made it possible to secure better results.

The spectroheliograph is an instrument by means of which any object may be photographed in monochromatic light. The construction of the instrument varies somewhat for different classes of work. A form which has proved very satisfactory for general solar investigations consists of a large, grating spectroscope provided with two movable slips — one at the focus of the collimator, the other at the focus of the observing telescope. These are connected by levers, and operated by hydraulic pressure in such a manner that when the K line of the fourth order spectrum of the grating is made to fall upon the second slit it remains there, no matter how the slits are moved. The photographic plate is placed with the sensitive surface almost in contact with the jaws of the second slit. In photographing the chromosphere and prominences it is only necessary to exclude the light of the sun's disk by a suitable diaphragm, and allow the first slit to move slowly across the solar image. The photograph is built up from a series of successive images of the bright K line.

The advantages thus afforded over the visual method of recording the varying forms of the chromosphere and prominences are numerous. Errors on the part of the observer are done away with, time is saved, and portions of the prominences too faint to be seen by the eye are obtained on the photograph. Such a picture can be made in two minutes, though better results are secured by limiting the width of the slits to about $\frac{1}{200}$ of an inch and giving an exposure of nearly twenty minutes. The most skilled observers require over an hour to sketch the sun's circumference through the C line, so the gain in time is no less evident than the gain in accuracy. Photographs of short-lived eruptions can be made at the rate of several per minute, and the substitution of a train of prisms for the grating would render possible much shorter exposures.

The series of photographs shown[1] illustrate the manner in which

[1] The paper was illustrated with the stereopticon.

prominences sometimes develop. It will be noticed that a streamer shot out nearly horizontally from a brilliant center of action far above the sun's limb, and finally descended to meet the chromo-sphere. The changes here recorded occupied thirty-four minutes.

Photographs of prominence forms in the F line show certain points of difference when compared with simultaneous photographs in the K line, principally in the greater extent of the region occupied by calcium.

WHITE PROMINENCES.

The question of the "white prominences" has naturally received attention. It will be remembered that at the eclipse of 1886 a prominence 150,000 miles high was shown in the photographs, and observed during totality. Neither before nor after totality could Professor Tacchini detect any trace of it with the spectroscope. A photograph of the spectrum taken by Prof. W. H. Pickering showed H and K with a bright, continuous spectrum, but none of the hydrogen lines seemed to be present. Such prominences are therefore invisible in visual observations through the C line, but they should be obtained in photographs taken with the spectroheliograph through the K line. As yet no such prominences have been detected on the Kenwood Observatory plates, though in most cases complete visual observations for comparison have been lacking. In the large number of photographs taken of prominence spectra, H and K have invariably been accompanied by the more refrangible hydrogen lines. A continuous spectrum has been photographed in the case of a few violent eruptions.

FACULÆ AND SPOTS.

The discovery at the Kenwood Observatory in December, 1891, that the H and K lines are invariably reversed in faculæ, opened a new field of application for the spectroheliograph. It is evident that the same procedure followed in the case of the prominences on the sun's limb will serve equally well for prominences or faculæ on the disk, provided only that they give sufficiently bright reversals of the calcium lines. In fact, the first photographs taken with the slit traversing the sun's disk showed the faculæ, not only near the limb — where alone they are visible in ordinary photographs or visual observations, — but also in the very brightest parts of the image. A

comparison of two photographs will illustrate this difference. One is a copy of a photograph of the sun taken at the focus of a photographic objective in the ordinary manner. The faculæ are shown only near the limb. It is from such photographs, which agree well with visual observations, that the accepted opinion of the condition of the sun's surface has been derived. From this point of view the spots are evidently the surface phenomena of first importance. But a glance at the next photograph, taken with the spectroheliograph, reveals an entirely different state of things. The faculæ are as clearly shown in the center of the image as at the limb; and the study of their relations with spots, their position and changing forms, once so difficult, now becomes easy. Since February, 1892, when the spectroheliograph was first successfully employed to photograph prominences and faculæ, over 2,600 negatives have been obtained with it. A record of the condition of the solar surface, as complete as the weather would allow, has thus been secured to supplement the series of spot photographs made in the ordinary way at Greenwich.

If the two pictures are closely compared it is seen that there are marked differences in the appearance of the spots. The faculæ almost invariably encroach on spot penumbræ, and small spots are frequently covered by masses of calcium faculæ. The great area covered by faculæ is surprising to any one accustomed to think of the solar surface as dotted with spots. M. Tacchini's visual observations of faculæ give the average total area as about equal to the average total area of spots. The present photographs show that the eye really perceives only a small fraction of the actual area covered by faculæ. It has also been found that small faculæ, less brilliant than those just referred to, mottle the entire surface of the sun, and extend from pole to pole. They are apparently parts of a continuous network which completely envelops the sun. This is somewhat delicate, and can only be well seen in the original negatives.

The forms assumed by faculæ are very peculiar, and in many cases decidedly suggestive. Sometimes the groups are very extended in a direction parallel to the equator, and the almost unbroken belts thus formed suggest planetary analogies, and perhaps refer to a past or future stage in solar evolution. Sometimes the groups are irregularly scattered over the disk. The changes of form are gradual, and ordinarily the configuration of a group is not materially altered in an interval of several hours. Examination of the plates has revealed a

distinct tendency in the faculæ toward curved forms. On 49 negatives taken on different dates, 245 cases of smooth curves in the forms of faculæ were noticed on casual inspection, and in 97 cases the curved faculæ terminated in bright circular heads, some of them containing minute spots. Spiral forms were found to be not uncommon; but the form which appears in the vast majority of cases is like that of a figure 3, usually with two, sometimes with three or more, loops. As everything points to the conclusion that the eruptive prominences spring from faculæ, the helical forms frequently observed or photographed in prominences may be associated with curved faculæ.

ERUPTIONS ON THE SUN'S DISK.

Perhaps the most interesting of the phenomena brought to light by the spectroheliograph are eruptions on the sun's disk. The celebrated observation by Carrington and Hodgson, in 1859, of two brilliant objects moving across a spot has never been exactly duplicated, but by the aid of the spectroheliograph eruptions invisible to the eye are sometimes recorded. A photograph of the sun, showing faculæ, spots, and prominences, was taken on July 15, 1892, at about 11.8 A.M. (Chicago M.T.), which showed nothing unusual in a spot in the southern hemisphere, except that the facula running between the northern and southern umbræ of the spot was brighter than usual. The next photograph, taken at about 11.20, showed a very different state of affairs. Extending between the umbræ, in a direction slightly inclined to the sun's equator, was a perfectly straight and exceedingly brilliant object, which expanded slightly at its eastern extremity, and turned sharply toward the north, terminating abruptly in a brilliant ball just east of the center of the northern umbra. The sudden formation of this remarkable object did not seem to affect the general group of faculæ surrounding the spot, for they remained of practically the same form as at first. As the plates were not developed immediately, nothing was known of the disturbance, and the next photograph was not taken until 11.47. Meanwhile an entire transformation had taken place in the luminous phenomenon, and so completely were the umbræ covered by the brilliant outbursts that they were no longer visible in the photograph. The straight tongue running between the umbræ in the first photograph had developed into an S-shaped form, similar in appearance to a facula shown in our photographs of

the great February, 1892, sun spot when on the eastern limb. Brilliant forms had also appeared to the northwest of the northern umbra, and the disturbance extended over an area of about four billion square miles.

Unfortunately no more exposures were made until 1.21, when eleven photographs of the spectrum of various parts of the spot region showed nothing out of the ordinary. A photograph of the sun exposed at 1.41 and another at 1.50 show the forms of the great region of faculæ surrounding the spot to be the same as they were before the disturbance, which had now completely disappeared.

Similar, though somewhat less extensive, eruptions have been photographed with the spectroheliograph on June 20, 1892, and January 26, August 3, 6, and 10, and September 14 of the present year. They have all occurred in the vicinity of spots, and have been of brief duration. In no case has the disturbance commenced in the umbra of a spot, nor have the surrounding spots and faculæ been materially altered in form by the outburst. It would then seem that we were dealing with true eruptions seen in projection. The forms are frequently more or less spiral, and recall the curved forms of faculæ already referred to. It is not impossible that the phenomena are those following the fall of meteoric matter into the sun; but if this were the case the chances would be against the invariable occurrence of the disturbance in a spot group, unless the group were supposed to exercise some attractive force on the meteoric mass. On the whole, the eruptive theory certainly seems preferable.

SOLAR DISTURBANCES AND TERRESTRIAL MAGNETISM.

The question as to the manner in which solar disturbances and terrestrial magnetic storms are related has long been under discussion, and its present condition is one of great uncertainty. The apparent existence of a twenty-seven-day period in the recurrence of magnetic perturbations is considered by some to indicate that disturbances in certain regions of the sun's disk — at the eastern limb or the central meridian, for instance — are alone capable of affecting the magnetic needle. To prove this it has been shown that the maxima of curves of magnetic intensity generally coincide with the appearance at the sun's central meridian of a spot or facula. Others have been no less successful in finding a spot or facula at the sun's eastern limb when-

ever an aurora is seen. To test whether these coincidences might not be due to chance, photographs of faculæ taken on one hundred and forty-two days in 1892 at the Kenwood Observatory were examined. It was found that for 1892 the probability that at any time one or more groups of faculæ would be on a given meridian of the sun was 0.93. Under such conditions it would be almost impossible for an aurora or magnetic storm to occur without the simultaneous existence of faculæ at either the central meridian or the eastern limb, and such coincidences must therefore be regarded as of doubtful importance.

As for the eruptions photographed on the solar disk, that of July 15, 1892, was simultaneous with "a slight trembling in the horizontal force magnet, which was the prelude to the violent storm which set in and lasted over the 16th and until midnight of the 17th." A similar though less important eruption shown on a spectroheliogram taken June 20, 1892, was not accompanied by a disturbance of the magnets, but a series of small oscillations commenced one day later, and lasted until June 26. Eruptions on January 26 and August 3 and 10, 1893, were without corresponding maxima on the magnetic curves. On August 6, 1893, there was a slight magnetic disturbance simultaneous with a small eruption.

THE GREAT SUN SPOT OF AUGUST, 1893.

The great sun spot which was a conspicuous object to the naked eye during the first two weeks of August last was remarkable in many ways, but especially for the fact that two eruptions were recorded in it by the spectroheliograph during its passage across the disk. On August 3, at 10.1 A.M., the group was an inconspicuous object near the sun's eastern limb. There are indications in the photograph of a disturbance in the faculæ south of the spot, and a plate exposed nine minutes later shows a brilliant eruption of strange form. From this time forth the spot group increased rapidly in size. It was preceded by a great area of faculæ, but not inclosed in one, as was the great sun spot of February, 1892. A photograph taken on August 5 shows what a great change the group had undergone in the interval of two days. This is especially noticeable in the following spot, which, on August 3, was small and covered by faculæ. On August 7 both spots and faculæ were still further developed, a bright bridge of faculæ had been thrown across one of the spots, and a small spot had broken out

in the faculæ preceding the group. The changes indicated on the photographs of the following day were confined principally to the faculæ surrounding the preceding member of the group. The bright bridge of faculæ had disappeared, and with it a mass of faculæ to the east, which before had covered two small spots. On August 9 all of the spots had become more regular in form, the faculæ were considerably changed in appearance, and once more nearly covered some of the smaller spots. One day later the two smaller groups into which the following spot had already divided were nearly equal in size. This segmentation seemed to be due to the formation on August 8 of a bright bridge of faculæ, which steadily increased in size. On August 12, when the group was near the western limb, the following spot was still further divided.

Such, in brief outline, is the history given us by monochromatic photography of the passage of a large spot group across the visible hemisphere of the sun. The numerous negatives secured each day will furnish material for a detailed study of the faculæ and their changes, and may lead us a step nearer to a true understanding of their origin.

NATURE OF THE FACULÆ.

Certain of the solar theories advocated at the present time explain the faculæ as phenomena secondary to the spots. Faye supposes the chromospheric matter to be drawn into the cyclone of the spot and released at the lower end of the funnel, where it receives new supplies of heat from the interior of the sun and forces its way to the surface, thus forming a ring of faculæ surrounding the spot. During the celebrated discussion of this and other solar theories recorded in the *Comptes rendus* of the French Academy, M. Tacchini naturally objected that this explanation did not suffice for faculæ not in the vicinity of spots. M. Faye replied that the entire body of the sun is covered with minute whirlpools, which maintain the supply of heat for radiation by causing a constant circulation of the chromospheric matter. When these pores are closely crowded together they produce faculæ, just as the spot does in the explanation already given.

The inadequacy of this explanation can hardly be doubted after an examination of even a limited number of spectroheliograms. While not yet made certain by a prolonged study of the plates, it seems more than probable that faculæ, and not spots, are the first evidences of

solar disturbances. But whether this be true or not, numerous cases might be cited in which groups of faculæ containing no spots, or at most small and insignificant ones, were far larger and more brilliant than faculous areas accompanying spots of the largest size. The photographs which illustrate the partial history of the great spot group of August last exhibited an excellent case of this kind. Moreover, no evidence has been advanced to substantiate M. Faye's hypothetical crowding of pores in regions of faculæ.

As to the nature, if not the cause, of faculæ there can be little difference of opinion. The spectroheliograms confirm what has long been known, that faculæ are elevations above the general level of the photosphere. Besides glowing with the continuous spectrum of the cloudlike photospheric matter, they exhibit the H and K radiations of calcium with marked intensity. The Kenwood Observatory photographs invariably show these bright lines divided with a dark line of absorption. Indeed, in some instances, there is a continuation of the doubly reversed line across a portion of the solar disk and into the chromosphere. Hence the faculæ, and sometimes large areas of the photosphere, show certain evidence of the presence of unbroken regions of extremely hot calcium vapor, capped with cooler vapor of the same kind. The prominences are not ordinarily clothed in such shells of cool calcium vapor, at least not in sufficient thickness to cause a second reversal of the lines. But occasionally a violent eruption brings out the double reversals in the lower parts of the resulting prominence, and the chromosphere at the limb invariably gives a double reversal like that of a facula. In sun spots the double reversal in the surrounding faculæ usually narrows down into a single bright line over the umbra. This is probably due to the chromosphere overlying the cooler region of the spot. It may also be pointed out that the bright H and K lines over spots are almost invariably of the type shown in this photograph. In the numerous photographs of this kind made at the Kenwood Observatory there are in a few instances a slight widening of the bright lines. In most cases the lines are undistorted and of normal width. Such immobility is hardly compatible with any theory requiring rapid downrushes or uprushes in spots.

Singularly enough, hot hydrogen does not seem to be a common constituent of faculæ. The F line is very rarely reversed in them, so that ordinarily no traces of the faculæ are shown in photographs of the sun made by setting the F line, instead of the K line, on the second slit of the spectroheliograph.

To inquire into the relations existing between prominences and spots and faculæ would prolong this paper beyond reasonable limits, and it will suffice to say that the spectroheliograph affords excellent material for such an investigation. A photograph from a single original negative showing all of the solar phenomena within our reach can be made in a very simple way by means of a double exposure.

The photographic record of prominences and faculæ hitherto obtained only at the Kenwood Observatory will shortly be supplemented by similar work in India. Prof. K. D. Nægamvala, director of the observatory at Poona, has decided to obtain a spectroheliograph, with which the sun will be photographed as frequently as possible. As the observatory is separated from Chicago by about 160 degrees of longitude, and is favored by clear skies during the greater part of the year, the solar record should henceforth suffer few serious interruptions.

The study of solar physics will never be altogether satisfactory, however, until photographs of the sun show not only faculæ and spots, and the chromosphere and prominences, but the corona as well. Still hidden in the glare of atmospheric light, the corona is revealed only on the occasion of a total eclipse, and knowledge gathered in such brief intervals of time is necessarily meager. The photograph on the screen represents an instrument on the principle of the spectroheliograph used on Pike's Peak a few months ago in an attempt to photograph the corona without an eclipse. Clouds of smoke from extensive fires in the forests surrounding the peak made a satisfactory test of the instrument impossible, and no images of the corona were obtained. It is hoped that the experiment may soon be repeated, though it must be admitted there is small chance of success. But in Italy and France, in England and America, this difficult problem is under investigation, and its solution may not be far distant.

THE REMOVAL OF PATHOGENIC BACTERIA FROM DRINKING WATER BY SAND FILTRATION.

By GEORGE W. FULLER, S.B., Biologist in Charge Lawrence Experiment Station.

Read November 9, 1893.

That drinking water is a carrier of some diseases there can be no doubt. Numerous laboratory experiments by many investigators indicate that the bacteria generally considered to be the specific organisms of typhoid fever, Asiatic cholera, and other diseases, live in ordinary drinking water for many days. The results of long-continued investigations at the Lawrence Experiment Station show that the typhoid bacillus continues to live in the water of the Merrimack River at Lawrence in greatly diminished numbers for a period of twenty-four days. Other investigators, using different water and different conditions, estimate the length of life of this germ at from three to eighty days. The duration of life of the cholera spirillum in various waters has been observed to be from two days to seven months.

Modern hygiene demands that drinking water shall be free from pathogenic bacteria, and the means by which such water can be obtained are worthy of our most careful consideration.

In some localities satisfactory supplies of pure water can be had from driven wells and from surface water taken from watersheds which are free from human habitation. It is very rare, however, that great cities with their large suburban population can obtain a sufficient quantity of perfectly safe drinking water from either of these sources. Many water supplies drawn from polluted sources have been introduced in America in recent years with the belief that the impurities were removed from the water on its passage to the consumers. It is true that a certain degree of bacterial purification is effected by dilution, by storage in a reservoir holding one or two weeks' supply, and

by passage under pressure through miles of iron pipe. But the experience of numerous cities, involving the loss of hundreds of human lives, shows conclusively that all of these conditions taken together are insufficient to render an infected water safe at all times for drinking purposes.

At the present time many cities and towns — and the number is constantly increasing — are obliged to face the problem, How can the pathogenic bacteria be best removed from a polluted water? From the results of long continued scientific investigations, together with the experience of certain European cities, it is fully believed that the requirements of modern sanitary science are satisfactorily fulfilled by properly conducted sand filtration.

Sand filtration was first introduced near London, by James Simpson, in 1839. It is the practice in Europe to pass the water through fields of thoroughly underdrained sand from three to five feet in depth. The surface of the sand is kept continually covered with water. The sediment in the unfiltered water is deposited on and very near the surface of the sand. This gradually increases the resistance to the passage of the water through the sand until a point is reached when the quantity of water yielded by the filter is so small that it is necessary to scrape the filter, that is, to remove the upper layer of clogged sand.

During the past forty years many filter plants have been constructed in Europe, and numerous improvements in the filtration of water have been made particularly during the past decade. This is largely due to the aid of bacteriology, which enables us to determine the actual efficiency of filters with regard to the removal of bacteria. The operation of some European filters is quite satisfactory, as is shown both by the low death-rates from those diseases conveyed by drinking water and by the results of numerous bacteriological investigations.

The water from the river Thames — the source of a part of the London water supply — was examined bacterially for several years by Prof. Percy Frankland before and after filtration. The average results for the years 1886, 1887, and 1888 showed an average removal of 97.6 per cent. of the bacteria in the unfiltered water. The average typhoid fever death-rate in London during these years was very low, namely, 1.6 per 10,000 inhabitants.

The operation of the Berlin filters has also been watched very

closely, particularly the works at the Stralauer Thor, which were under the direction of Piefke, the eminent engineer, with whom it was my privilege to study for a short time. Through the investigations of Piefke and the bacteriologists of the Hygienic Institute at Berlin, our knowledge upon the removal of bacteria from water by sand filtration has been much extended.

In 1887 the State Board of Health of Massachusetts established an Experiment Station at Lawrence. The object of this was to study the laws of filtration. The Experiment Station was designed by Mr. Hiram F. Mills, A.M., C.E., the distinguished engineer, who has directed the investigations. During the earlier history of the work attention was devoted chiefly to sewage filtration. The fact that typhoid fever has been epidemic from time to time in certain Massachusetts cities gave an increased impetus to the study of water filtration during the past two years.

In the fall of 1887 a tank 6 feet deep and 17 feet 4 inches in diameter was filled with mixed coarse and fine sand and a layer of fine loam 8 inches thick, the top of which was 6 inches below the surface. The total depth of the filtering material was 5 feet. Beginning in January, 1888, water from the Merrimack River, which had passed through the reservoir and service pipes of the Lawrence Water Works, was applied to this filter sixteen hours a day. The filter was allowed to drain during the rest of the time and the pores of the sand fill with air. Such a filter is known technically as an intermittent filter, in distinction from the continuous filters the surfaces of which are constantly covered with water.

The number of bacteria in the effluent of this filter was very low, usually below ten per cubic centimeter, and at times it was sterile. In May, 1891, elaborate preparations were made to settle with certainty whether any of the bacteria found in the effluent came down through the filtering material with the applied water, or whether they had their origin in the underdrains according to the theory of Bertschinger and other Europeans. The greatest care was taken to prevent contamination of the effluent by air and dust. The average results of 186 bacterial determinations indicated that from May to October, 1891, the applied water contained 175 and the effluent 4.7 bacteria per cubic centimeter. This was a removal of 97.3 per cent. of the bacteria in the unfiltered water.

To obtain more definite knowledge upon the subject, river water

taken directly from the canal was applied to the filter, commencing November 13, 1891. Repeated determinations of the bacteria in the river water and in the effluent were made daily on the same nutrient gelatine, grown for the same length of time and at the same temperature. Many duplicate determinations were made, and it was found that no further development occurred when the plates were allowed to stand six and even eight days. Quantitative determinations of the species of bacteria in the filtered and unfiltered water were made at frequent intervals. One of the most striking results of this work was that *B. coli communis*, the leading species in human fæces, was found during November and December, 1891, to form 39 per cent. of the bacteria in the water of the Merrimack River at Lawrence. This species of bacteria, however, was not found in the water after its passage through the filter.

The results of the investigation upon the removal of bacteria by this filter may be summarized as follows:

1. The application of river water instead of city water, which increased the number of applied bacteria more than tenfold, was followed by no increase whatever in the total number of bacteria in the effluent of this filter.

2. Of the 102 bacterial determinations of the effluent from November 14 to December 31, inclusive, 58 indicated that the filtered water was sterile.

3. No relation could be found between the rate of flow of the water through the filter and the number of bacteria in the effluent.

4. As a result of numerous species determinations it was found that three of the most prominent kinds of bacteria in the river water were not present in the filtered water. Among these species was *B. coli communis*, which is the leading species in fæces, and which resembles in many ways the bacillus of typhoid fever.

5. The presence of the very small numbers of bacteria in the effluent was satisfactorily explained by their specific similarity to those present in the air, the outlet pipes, and the underdrains.

From this evidence it was concluded that with these filtering materials and under these conditions all the bacteria of the Merrimack River water may be removed by filtration.

This filter was continued during the following year, and the degree of bacterial removal remained most satisfactory. The maximum

amount of water purified by this filter has not exceeded 250,000 gallons per acre daily. The adoption by cities and towns of water filtration through such materials would be very costly; and a large portion of our attention has been devoted to the study of filtering materials coarse enough to filter a municipal water supply economically, while removing the pathogenic bacteria.

Fourteen new experimental water filters were constructed during 1892. The construction and operation of the filters were such as to throw as much light as possible upon the laws of filtration. Since the removal of bacteria is one of the most important points in the filtration of water, the investigations were arranged so as to allow direct comparison of the power of removal of bacteria from water under different rates of filtration, with sands of different degrees of coarseness, with different depths of the same sand, with the presence of loam layers, and with intermittent and continuous filtration.

The actual efficiency of the filters was tested by the application of typhoid fever germs, as well as other prominent species, and observations upon their passage through the filters. The pure cultures of the microörganisms were grown in dilute bouillon solutions, and 25 or 50 cubic centimeters of these solutions containing millions of germs were applied usually in a gallon of water to the filters. The course of the dose through the filters was followed in many cases by adding a small quantity of common salt with the dose and examining the effluent for chlorine. Bacterial examinations of the effluent were made at frequent intervals for several days.

It is obviously impossible to discuss here in detail the results which are presented in the several reports of the Board, and it is the purpose in the present paper to outline the methods of investigation and summarize the results.

During the first five months of 1892, fifty-five experiments upon the passage through the filters of pure cultures of bacteria in single doses were made with results which are summarized as follows:

TABLE NO. I.

Filter No.	Number of experiments.				Number of bacterial determinations.	Number of bacteria per cc. applied.	Per cent. removed.
	Typhoid.	B. prodigiosus.	B. coli communis.	Total.			
18 A	3	1	0	4	131	142,600	99.56
35	3	0	0	3	41	3,630	100
36	3	0	0	3	46	9,270	100
33 A	0	1	1	2	25	275,000	100
34 A	0	1	1	2	25	227,000	100
35 A	4	2	2	8	146	77,630	98.02
36 A	3	2	2	7	136	145,800	99.33
37	1	4	2	7	105	121,000	99.999
38	1	2	2	5	73	44,500	99.80
39	2	3	2	7	93	42,800	99.09
40	2	3	2	7	93	57,000	98.43
Averages and totals	22	19	14	55	914	104,200	99.48

These experiments were very severe tests upon the efficiency of the filters in removing bacteria, because the number applied was probably greater than would occur in practice, and, furthermore, the organic matter introduced with the bacteria served them as a food material. The experiments made during the latter portion of the year are much fairer, because the bacteria were applied in small and long-continued doses at frequent intervals and less organic matter was put into the filters. Pure cultures of the different species of bacteria were obtained by inoculation and growth for four days at 20°C. in solutions of one tenth per cent. peptone and two tenths per cent. glucose in city water. It was found that this solution contained on an average about 20,000,000 bacteria per cubic centimeter. This solution was applied to the filters, in the proportion of one part to three thousand parts of water, at intervals of one or two hours, according to the rate of filtration. Every cubic centimeter of water which went into the filters during the experiments contained, as a rule, about 6,000 bacteria of the pure culture in addition to those water bacteria ordinarily present. It was determined, also, that the food material which was applied with

these germs did not increase the organic matter in the river water beyond the limits of variation which have been occasionally observed in it from month to month. Table No. II contains the average results of five analyses of the river water before and after adding to it this solution.

TABLE NO. II (parts per 100,000).

	Free ammonia.	Albuminoid ammonia.	Chlorine.	Nitrogen as		Oxygen consumed.
				Nitrates.	Nitrites.	
River water before inoculation .	.0056	.0172	0.19	.015	.0001	.52
River water after inoculation .	.0062	.0203	0.19	.015	.0001	.54

B. prodigiosus is the species of bacteria which has been used since September, 1892, almost without exception in these experiments. The reasons for using this species are: (1) the ready and accurate means for its differentiation; (2) its great similarity to *B. typhi abdominalis* in its mode of life in the river water — neither species multiplies, but both continue to live in greatly diminished numbers for fifteen to twenty days or more; (3) the fact that it has never been found native in this country, and we are therefore reasonably sure that the bacteria of this kind, when found in the filtered water, must have passed through the filter from the applied dose.

Beginning September 16, 1892, repeated doses of *B. prodigiosus* were applied at frequent intervals for ten hours daily to the several water filters. Throughout the experiment, from September 16 to December 31, four examinations were made daily of each of the effluents at times when the applied doses were passing through the outlet pipes.

In Table No. III is presented a summary of the average results of the daily application of *B. prodigiosus*, together with the depths of the filters and the average rates of filtration.

TABLE NO. III.

Filter No.	Depth of filter. (Feet.)	Rate of filtration (Gallons per acre daily).	Number of bacterial determinations.	Average number of B. prodigiosus per cc. applied.	Per cent. removed.
18 A	5	1,300,000	160	3,660	99.84
33 A	5	1,700,000	212	5,710	99.78
34 A	5	1,500,000	260	7,630	99.83
35 A	5	1,200,000	120	8,780	99.95
36 A	5	2,400,000	288	6,220	99.96
37	5	1,700,000	152	3,370	99.94
38	2	1,800,000	288	4,700	99.86
39	1	1,900,000	364	6,230	99.83
40	1	1,700,000	128	3,630	99.91
41	5	1,700,000	144	4,175	99.97
42	1	1,800,000	256	8,060	99.73
Average and totals .	....	1,700,000	2,372	5,700	99.87

Numerous determinations have been made of the ordinary water bacteria present in the unfiltered and filtered water. Beginning in June, 1892, all of the effluents have been examined once a day or oftener. As was indicated by the investigations upon Filter No. 8, the true degree of bacterial removal is somewhat obscured by the presence in the effluents of bacteria which do not appear to come down through the filter, but seem to have their origin in the underdrains, where they continue to live upon the very small amount of food present.

In Table No. IV is given a summary of the total averages of these results, including the bacterial examination of more than 5,000 representative samples of unfiltered and filtered water.

TABLE NO. IV.

Filter No.	Bacteria per cc. in river water.	Per cent. removed.
8	5,300	99.83
18 A	9,960	99.22
33 A	8,410	99.29
34 A	9,160	99.57
35 A	9,310	99.45
36 A	8,510	99.27
37	8,540	99.34
38	8,860	99.03
39	8,810	99.01
40	9,010	99.26
41	10,050	99.51
42	8,750	97.74
Averages	8,780	99.21

As has been stated already, the sediment in the unfiltered water is deposited upon and very near the surface of the sand. The surface sand in time becomes so clogged that it is necessary to scrape off $\frac{1}{8}$ to $\frac{1}{4}$ of an inch. When the experimental filters are to be scraped the water above the surface of the sand is removed with a siphon and the filter allowed to drain until the water lowers to about an inch below the surface of the sand. After scraping, the water is applied to the filters from the top. In Berlin it is believed that the efficiency of the filter depends upon the scum which is formed on the surface of the sand. In some places abroad it has been found that the effluent contains at times as many bacteria as the unfiltered water just after scraping. At Lawrence the efficiency of the filters in removing bacteria, under the existing conditions of operation, varies but very slightly during the period between scrapings. This is brought out very clearly by Table No. V, in which are given the average results of the bacterial examinations of the effluents for the three days before and the three days after scraping. They extend over the period from September 16 to November 27, when the several filters were running under nearly the same conditions before and after scraping. During

this time the number of ordinary water bacteria in the applied water averaged 13,600, and the number of *B. prodigiosus* for the ten hours of daily application, 6,400 per cubic centimeter.

TABLE NO. V.

Number of filter.	Water Bacteria.			B. Prodigiosus.		
	Number of scrapings.	Number during the three days before scraping.	Number during the three days after scraping.	Number of scrapings.	Number during the three days before scraping.	Number during the three days after scraping.
33 A	3	31	45	1	0	3.0
34 A	5	32	42	4	0.4	0.4
35 A	4	50	77	3	1.0	3.3
36 A	4	39	52	4	3.9	6.8
37	2	21	48	1	0	0.5
38	6	47	121	4	4.2	11.6
39	8	52	90	8	3.6	7.3
40	3	48	29	3	1.3	2.3
41	5	20	28	2	0.4	1.4
42	2	109	233	2	13.0	34.0
Totals and averages . . .	42	44	75	32	2.8	6.7
Average per cent. removed,	....	99.68	99.45	....	99.96	99.89

These results indicate that there are more bacteria in the effluent after scraping, but the increase forms only a small fraction of 1 per cent. of the applied bacteria. With coarser sands and higher rates of filtration this difference would probably become more marked.

The cause of the differences in the results at Lawrence and in Europe is not clear, because our comparative knowledge of the existing conditions is incomplete. The nature of the unfiltered water as well as the physical characteristics of the sand with which a filter is filled exert an influence upon the efficiency of filtration. Not only the absolute size but the relative sizes and the shape of the sand grains has an important bearing. Suppose we have two filters, each filled with sand grains of equal volume, but in one case in the form of cubes and in the other in the form of spheres; it is perfectly clear that very different results would follow. In Germany it is the practice, in some places at least, to wash out the finer particles before placing

the sand in the filter. This is not done at Lawrence. Samuelson, the chief engineer of the Hamburg Water Works, states in a recent paper that the best filtering sand is one in which all the grains are approximately one millimeter in diameter, and that the operation of the filter is much different if the sand is but little finer. The Lawrence results indicate that it is the finer particles of sand which determine its efficiency, for the reason that the finer grains fill up in part the spaces between the coarser grains.

It may be said, in passing, that an important feature of the work at Lawrence is the study of the physical properties of materials which govern their actions as filters. Great assistance has been obtained from relations already formulated. The effective size of a sand is considered as the maximum diameter of the finest 10 per cent. of the grains. The effective size of the most efficient experimental filters at Lawrence, that is, those which yield the most water between scrapings while removing substantially all of the bacteria, lies between 0.2 and 0.3 of a millimeter.

But, disregarding the true and entire explanation of the differences, the fact remains that the Lawrence filters are a greater safeguard than some European ones in the removal of pathogenic bacteria from drinking water, because their efficiency is more uniform.

It is to be stated in the case of the Lawrence filters, that it is the upper portion of the sand that largely accomplishes the bacterial purification. This is shown most clearly by Table No. VI, in which are given the numbers of bacteria per gram found in the sand at different depths of a continuous filter which had been in operation from May 2 to October 26, 1892. This filter was scraped on October 15, and was again clogged on October 26, the date of examination.

TABLE NO. VI.

Depth from surface (inches).	Bacteria per gram.
0 — ¼	1,100,000
½	320,000
1	140,000
2	21,000
4	4,000
6	1,600

During the past year the city of Lawrence has constructed a large water filter, which has recently been put in operation. This filter, which was designed by Mr. Hiram F. Mills, is $2\frac{1}{2}$ acres in area and has a capacity of 5,000,000 gallons daily. Its construction is based upon the results obtained at the Lawrence Experiment Station. This filter, the only one of its kind in America, differs chiefly from those in Europe in that it is operated intermittently and the pores of the sand allowed to fill with air every day. This facilitates the oxidation processes and appears to have an advantage over continuous filters, because it removes more of the organic matter which accumulates at the surface of the sand.

With regard to its removal of bacteria from the river water, it may be stated that the efficiency compares very favorably with that of the experimental filters of similar construction. During the second week of operation the removal of bacteria from the river water was as high as 98 per cent.

In studying the death-rates of the large cities of the world which draw their drinking water from polluted sources, it is very clear that a great safeguard against certain diseases conveyed by drinking water is afforded by sand filtration. Thus London and Berlin, with originally polluted but filtered drinking water, had typhoid fever death-rates in 1891 of 1.3 and 1.0 per 10,000 inhabitants respectively; while, on the other hand, Chicago and Philadelphia, which use polluted and unfiltered water, had during the same year typhoid fever death-rates of 16.0 and 6.4 per 10,000 inhabitants respectively.

The most striking example of this point is the experience with cholera at Hamburg and Altona. This is probably familiar to all, but as it illustrates the point so well I shall outline it briefly.

Hamburg and Altona are on the river Elbe. Hamburg drew its water from the river above the city. Nominally the Hamburg water was purified by the use of settling basins. The system was overworked, however, and there was practically no settling at all. The city of Altona takes its water from the river below the outfall of the Hamburg and Altona sewers, but before using carefully filters it through sand. Wandsbeck, a neighboring city, receives its supply from an inland lake, and also employs sand filtration. During the cholera epidemic of 1892 Hamburg, with its unfiltered water, suffered severely; with a population of 622,530, it had 17,975 cases and 7,611 deaths from Asiatic cholera. Altona and Wandsbeck, on the other hand, supplied

with filtered water, suffered but little at this same time from cholera. Altona, with a population of 143,000, had 562 cases and 328 deaths; Wandsbeck, with a population of about 20,000, had 64 cases and 43 deaths. There is every reason to believe, moreover, that the cases which did occur in the two latter cities were imported from Hamburg, and were not due to local causes. German sanitarians also call attention to the fact that in a street which is a dividing line between Hamburg and Altona, the people on one side using Hamburg water fell victims to cholera, while their neighbors across the way using Altona water were free from this disease.

In summing up our present knowledge upon the removal of pathogenic bacteria from drinking water, we may state that, in addition to the experience of certain European cities, the Lawrence investigations, covering a period of more than five years and including the bacterial examination of more than 11,000 samples of water, indicate that it is entirely practicable to construct filters which will purify water economically and remove more than 99 per cent. of the bacteria in the unfiltered water.

THE METROPOLITAN SEWERAGE SYSTEM.[1]

By HOWARD A. CARSON, Engineer Metropolitan Sewerage Commission.

Read December 14, 1893.

The cities, towns, and separate districts of Boston proper, Cambridge, Charlestown, Somerville, Chelsea, East Boston, Brookline, Brighton, Everett, Winthrop, Watertown, Newton, Waltham, Malden, Melrose, Stoneham, Winchester, Woburn, Medford, Arlington, and Belmont are grouped closely together, as is well known. Excluding Boston proper, South Boston, and some other districts tributary to the intercepting sewers mainly completed nine years ago and shortly to be alluded to, they have an area of about 130 square miles and had a population in 1890 of 395,326.

The eight cities first named have had sewers for a long time; the next six towns and cities have had sewers for a few years; the others have few or none, but probably will have in the very early future. The eight cities first named discharge their sewers, except so far as they have been intercepted, into the nearest estuary, basin, or other tide water. Large areas of mud flats were uncovered by the low tide and gave off during much of the year offensive smells. Years ago this condition of things gave strong offense to the citizens of this area, and it was believed to be dangerous to the public health. Boards of health, many physicians, and other citizens remonstrated, and the question of affording relief was vigorously agitated. In 1875 a commission consisting of Civil Engineers E. S. Chesbrough and Moses Lane and Dr. Charles Folsom outlined a scheme of relief. They proposed two main drainage systems: one for that part of Boston south of the Charles River and for Brookline, having its outlet at Moon Island; another for Cambridge, Somerville, Charlestown, Chelsea, and East Boston, having its outlet at Shirley Gut.

[1] This sketch was prepared in the midst of pressing work. In making it the writer borrowed freely from his annual and other reports.

A portion of the former system, somewhat modified in route, was adopted. Work was begun upon it in September, 1877, and between six and seven years later it was partly completed and put in operation. This system is known as the Boston Main Drainage. It consists essentially of intercepting sewers which pass nearly around the peninsulas of Boston proper and South Boston and discharge into a trunk sewer which leads to Old Harbor Point. The intercepting sewers are low enough to intercept the flow of sewage in the local sewers, and are mainly lower than the mean low water of the sea. The sewage so intercepted flows to the pumping station at Old Harbor Point, and is there lifted high enough to be discharged at high water into the sea at Moon Island. The system embodies the fundamental ideas of the London system of intercepting sewers and main drainage completed nearly thirty years ago.

The Metropolitan Sewerage System is of a similar character. In its general features it is like that proposed by the commission of Chesbrough, Lane, and Folsom already referred to, but it takes the sewage from fourteen additional towns and cities. It consists, in reality, of two systems — one for Waltham, Newton, Watertown, Brighton, Brookline, and a part of Boston whose most easterly point is at the corner of Huntington Avenue and Gainsborough Street. This trunk sewer is a little over eight miles long and lies wholly south of the Charles River. It connects with the Boston system and finds an outlet at Moon Island. The much more extensive North Metropolitan System lies wholly north of the Charles River, and a considerable part of it lies north of the Mystic River. It has an outlet about one third of a mile south of the southerly end of Deer Island, or about a mile and a half beyond Shirley Gut outlet, proposed by the Chesbrough Commission.

Between 1875, which was the year of the Chesbrough Commission, and 1887 various studies were made by able commissions and able engineers for disposing of the sewage of the towns and cities outside of Boston proper here referred to. All of these studies helped to contribute to the final result. I cannot now take the space to further refer to them. In 1887 the matter was referred by the Legislature to the State Board of Health. This board considered three separate schemes — one for the discharge of crude sewage into a strong tidal current, whence it would be carried to sea beyond return; one for clarification by chemicals; and one for ground filtration. Three en-

gineers were engaged to each study one of the foregoing schemes. The writer was placed in charge of the studies of the first one.

The board finally concluded that the second scheme was too costly and not sufficiently effective and that the third would be impracticable; and they reported to the Legislature in January, 1889, in favor of the first scheme, which was estimated to cost, in round numbers, five million dollars.

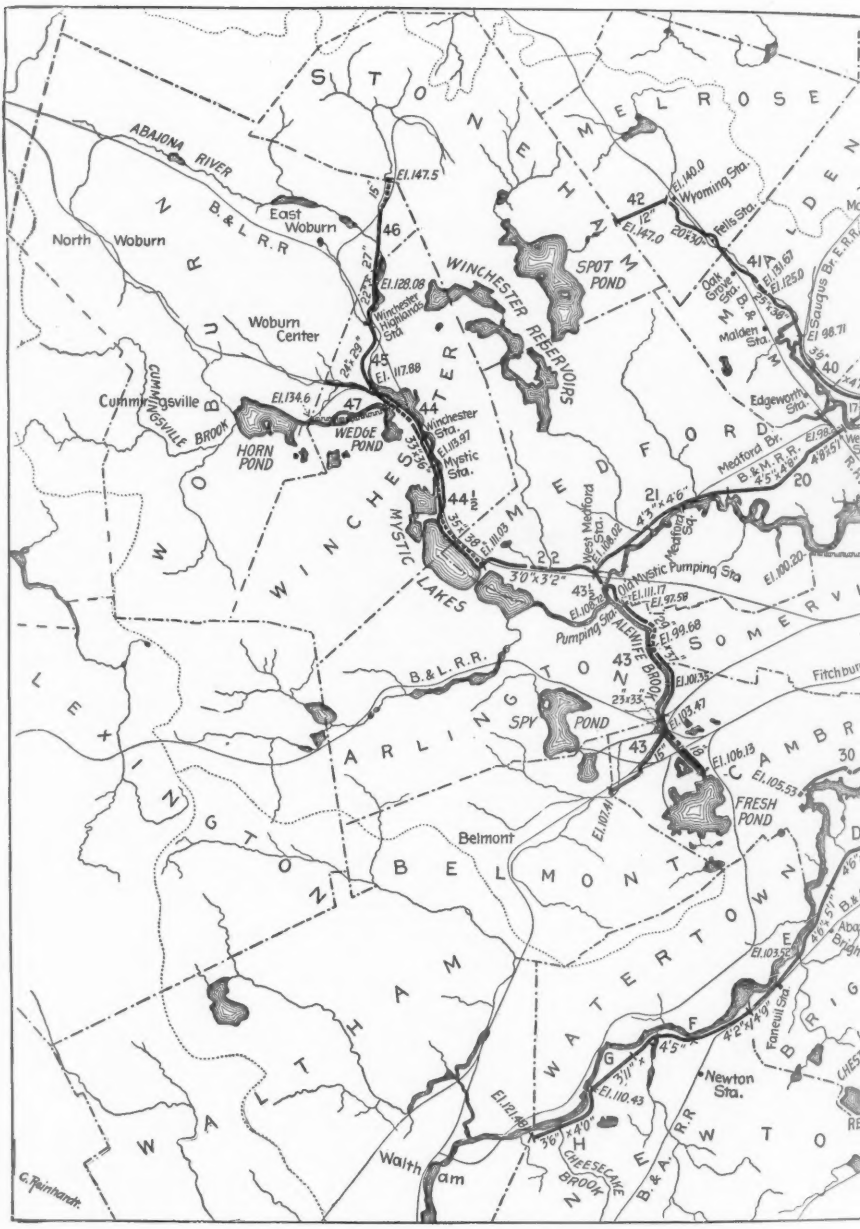
The Legislature passed an act, approved June 7, 1889, for a commission of three able and discreet men, to be appointed by the governor, to construct the Metropolitan Sewerage System substantially in accordance with the plan recommended. The Board of Metropolitan Sewerage Commissioners as at first organized consisted of Hosea Kingman, Tilly Haynes, and Dr. Robert T. Davis. In March, 1892, Harvey N. Collison succeeded Dr. Davis. The board organized in September, 1889, and engaged the writer as engineer in the latter part of October. The winter and spring of 1889–90 were spent in making surveys, studies, and plans. The work of construction began the latter part of May, 1890.

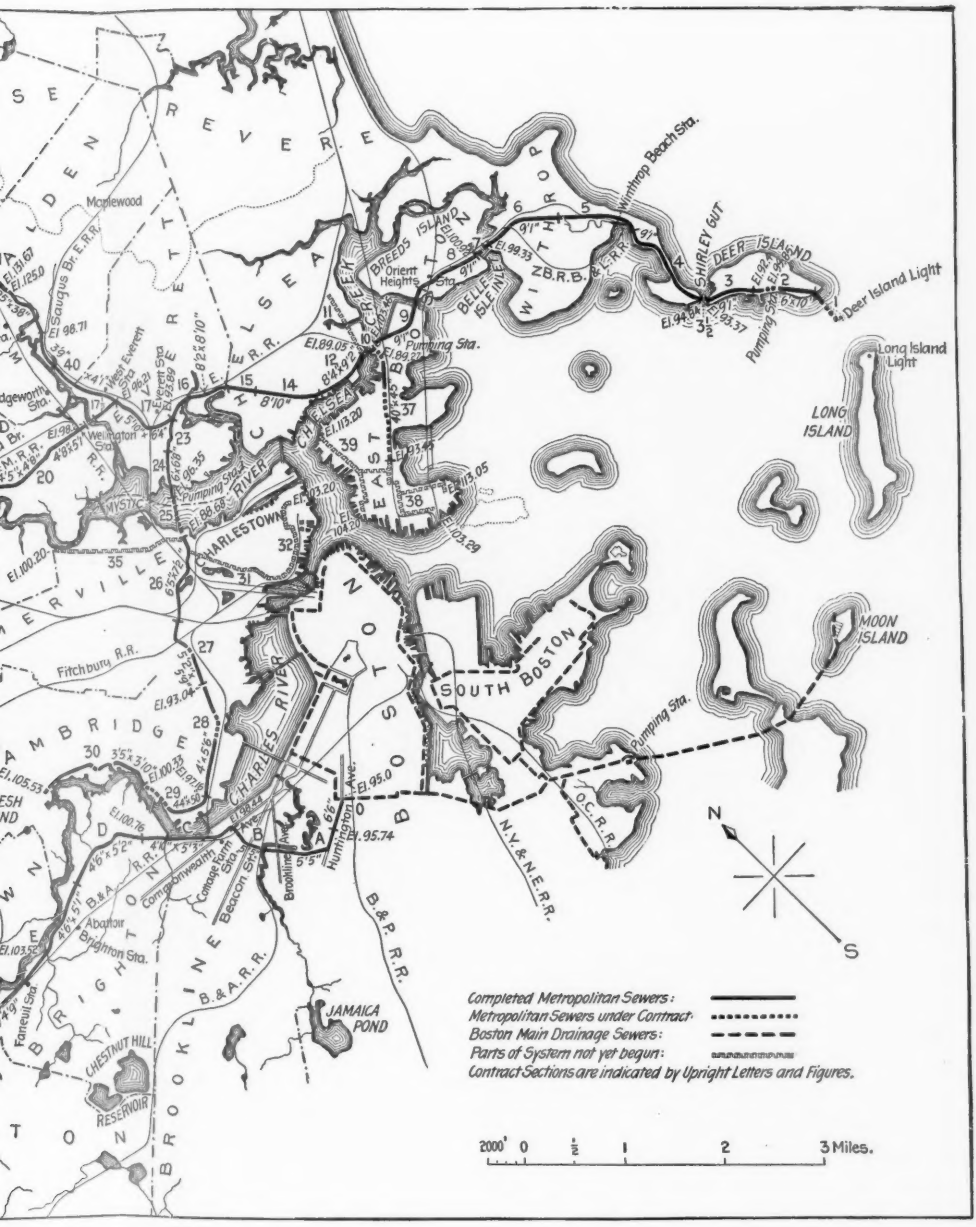
The Metropolitan Sewer is designed to carry mainly house sewage. Its capacity is based on the estimated population in the year 1930, and is about 225 gallons per head per day for that population. If it were to be made large enough to take roof water at the rate, say, of two and one half inches in five hours from the territory tributary to it, its carrying capacity would have to be increased between four and five times; and if it were designed to carry rain water from the whole surface, it would, of course, have to be much larger still.

The Metropolitan Sewer south of the Charles River has at Gainsborough Street, in Boston, a diameter of six feet six inches, which gradually diminishes in size, and eight miles above, at Waltham, is only three feet six inches by four feet in diameter. It has a fall most of the way of about two feet to the mile. The Charles River line was completed early in the spring of 1892, and has been in operation ever since.

The North Metropolitan System is now so far advanced that it may possibly be completed and in operation by the end of the following year.

The North Metropolitan Sewer for the lower five miles has an average diameter of a little more than nine feet, and has a fall of about one and three quarters feet to the mile. This system has various


STONEHAM
MELROSE
ABAJONA RIVER
B. & L. R.R.
North Woburn
East Woburn
El. 147.5
El. 140.0
Wyoming Sta.
El. 147.0
Fells Sta.
WINCHESTER RESERVOIRS
SPOT POND
Winchester Highlands Sta.
El. 128.08
Woburn Center
El. 117.88
Oak Grove Sta.
El. 135.0
Malden Sta.
El. 98.71
Edgeworth Sta.
Medford Br.
B. & M. R.R.
CUMMINGSVILLE BROOK
Cummingsville
El. 134.6
WEDGE POND
HORN POND
Winchester Sta.
El. 113.97
Mystic Sta.
WINCHESTER
MEDFORD
WOBURN
MYSTIC LAKES
West Medford Sta.
Medford Sq.
Mystic Pumping Sta.
El. 100.20
El. 111.17
El. 92.58
Pumping Sta.
ALEWIFE BROOK
El. 99.68
SOMERVILLE
B. & L. R.R.
Fitchburg
SPY POND
El. 103.47
El. 101.35
El. 106.13
El. 105.53
CAMBRIDGE
FRESH POND
Belmont
El. 101.41
LEXINGTON
ARLINGTON
BELMONT
WALTHAM
WATERTOWN
Faneuil Sta.
Newton Sta.
El. 110.43
El. 121.48
CHESTNUT HILL RESERVOIR
CHESECAKE BROOK
Waltham
B. & A. R.R.
NEWTON
C. Reinhardt


Maplewood
Winthrop Beach Sta.
Shirley Gut
Deer Island
Deer Island Light
Long Island Light
Long Island
Moon Island
Breeds Island
Orient Heights Sta.
Belle Isle Inlet
Pumping Sta.
Chelsea Creek
Chelsea
Charlestown
Mystic River
Charles River
South Boston
Fitchburg R.R.
Commonwealth Ave.
Beacon St.
Brighton Sta.
Chestnut Hill Reservoir
Jamaica Pond
B. & A. R.R.
B. & P. R.R.
N.Y. & N.E.R.R.
B. & A. R.R.
Brookline
Allston
Brighton
Cambridge
Somerville
Revere
Winthrop
Boston
Completed Metropolitan Sewers:
Metropolitan Sewers under Contract:
Boston Main Drainage Sewers:
Parts of System not yet begun:
Contract Sections are indicated by Upright Letters and Figures.
2000' 0
1
2
3 Miles.
N
S

branches. One begins in Stoneham, in Montvale Avenue, near Oakland Station, about eighteen miles from Deer Island, where it is to receive most of the sewage from Stoneham. It follows down the valley of the Abbajona River to a point below Winchester, and then in the bed of the old Middlesex Canal to a point near the dam between the upper and lower Mystic lakes. Here it is joined by the old Mystic Valley Sewer, built some fifteen years ago by the city of Boston. The Cummingsville Branch (to be built by the board) will discharge into the old sewer. This old Mystic Valley Sewer has been purchased by the board and adopted as part of the system, to take most of the sewage from Woburn and some from Winchester. The Metropolitan Sewer continues down the valley near the Lowell Railroad to West Medford. At West Medford it receives the Alewife Brook Branch, which is designed to take the sewage from Belmont, Arlington, and part of that from Cambridge, Somerville, and Medford. Continuing through Medford, the Metropolitan Sewer receives at Wellington the so-called Edgeworth Branch, and will there take the sewage from Edgeworth and the west side of Malden.

The Metropolitan Sewer passes under the Malden River by a depressed curve or inverted siphon and joins, near East Everett Station, the branch from Stoneham, Melrose, and Malden. About three quarters of a mile further on, in the marsh near the Everett Station, it joins the so-called Cambridge Branch, which is designed to take the sewage from Cambridge, Somerville, Charlestown, and parts of Medford and Everett. It then passes through a part of Chelsea and around a part of the water front. Near Eastern Avenue it receives a branch, which is to intercept certain Chelsea sewers discharging into Chelsea Creek north of the railroad bridge. The sewer then passes by a siphon under Chelsea Creek to the proposed pumping station in East Boston. At this pumping station is received the system of intercepting sewers from East Boston, and the sewer here takes an upward step of sixteen feet. It then passes through a part of East Boston proper and Breed's Island, and under Belle Isle Inlet by another siphon; passes through Winthrop, under Shirley Gut by another inverted siphon; and continues on its way to the middle of the western shore of Deer Island. Here another pumping station is reached and the sewage is to be lifted to such varying heights as are necessary to discharge into the sea at different stages of the tide. The outfall sewer from this station continues near the western shore

of Deer Island to its southerly end, and then passes about two thousand feet out into the sea to a point where the sewage is to be discharged.

The so-called Cambridge Branch begins in Mount Auburn Street, Cambridge, some fifteen miles distant from the Deer Island outlet. The route of this Metropolitan Sewer lies mostly in streets near the bank of the Charles River. It will pass under and intercept the sewers which now discharge into that river. It passes under the McLean Asylum grounds in Somerville, and in Sullivan Square, Charlestown, it receives the Charlestown Branch. At Arlington Street, near Alford Street, it will receive a branch designed to take the sewage from parts of Medford and Somerville. The route next lies under the Mystic River on the east side of the Malden Bridge. Near the middle of Mystic River there is to be a pumping station, where the sewage will be lifted about nine feet.

The general route of the sewers is indicated upon the map. The sizes and the elevations above the datum plane are also indicated. The datum plane in question lies about one hundred feet below mean low water of Boston Harbor.

LOCATION OF PUMPING STATIONS.

There are four pumping stations on the North Metropolitan System — the three already alluded to and a small one on the Alewife Brook Branch in Somerville, near West Medford. The question has been asked, "Would it not be a better arrangement to concentrate all these pumping stations at Deer Island?" The discharge of the sewage is to be into the sea, whose average high level is about the same as the salt marshes which are everywhere to be seen about Boston. In order that the sewage shall flow towards the outlet the hydraulic gradient of the sewers must have an inclination in that direction. If the ground on which the dwellings are placed were high enough and sloped towards the sea, pumping might, of course, be dispensed with altogether. As a matter of fact, however, much of the district miles away from Deer Island is lower than Deer Island itself. The Metropolitan Sewer, for instance, where it passes under the local sewer in Hawthorne Street, Cambridge, near the Charles River, is only four feet above the mean low level of the sea, and from its inclination it of course gets lower and lower as we pass in the direction in which the sewage flows.

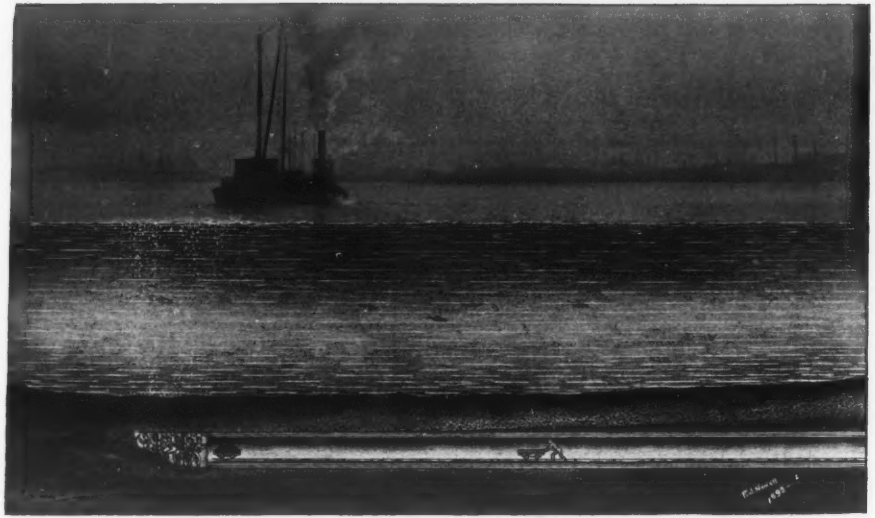


FIGURE 1. MYSTIC RIVER SIPHON, SECTION 25.

If there were no lift at Charlestown the three miles of sewer between that point and East Boston would be eight feet deeper than at present. This stretch of sewer already has an average depth of about twenty-five feet, and the cost of excavation if made eight feet deeper would be enormously increased. If the sewer still kept on, without a pumping station at East Boston, all that portion between East Boston and Deer Island would be twenty-four or twenty-five feet deeper than at present. The increased cost of the sewer placed so much deeper would have been counted by hundreds of thousands of dollars. The saving in cost of construction, however, is not the whole advantage gained by separating the pumping stations. Without such separation the work of pumping would have been very much increased; for it is clear that all the sewage from districts west of the East Boston Pumping Station, except that from Cambridge, Somerville, and Charlestown, would have been allowed to fall eight feet lower than as now arranged, and forever be pumped from this eight-feet lower level, and that all of the sewage from districts east of the East Boston Pumping Station would have to be pumped from a depth twenty-four feet greater than is necessary by the present arrangement.

It is thus seen that the use of several pumping stations does not increase the total work of pumping measured in foot pounds or otherwise, but, on the contrary, largely decreases it. A further advantage is that the comparatively low lift at each place allows the use of centrifugal pumps. In the matter of weight, space, liability to accidents, and especially in cost of pumps and cost of foundations and buildings, the advantages are in favor of centrifugal as compared with reciprocating pumps. The former, also, from the absence of valves, are better adapted to pumping sewage. Taking into account interest and depreciation on plant and buildings, as well as consumption of fuel and all other items of expense, it is found in the case under consideration that three low-lift stations with centrifugal pumps are at least as economical as one high-lift station with reciprocating pumps. It has already been shown that the cost of sewers in the former case is very much less. Studies were also made for concentrating the pumping at East Boston and using either force mains or a high masonry sewer between East Boston and the point of discharge. It was concluded that the cost of each of these latter designs would have been as great as the cost of the deep sewer and concentration at Deer Island previously alluded to, and with the disadvantage that neither

would be available for taking the sewage from points east of the East Boston Station.

RESERVOIRS AND DIRECT CONTINUOUS DISCHARGES.

The sewage from the Boston Intercepting System is not continuously discharged. There is a reservoir at Moon Island in which the sewage is stored during the flood and portions of the ebb tide. It seems probable that a reservoir will not be needed on the North Metropolitan Sewerage System for years, if at all. Deer Island is about two and one half miles nearer the ocean, measured in the direction of the current, than the outlet of Moon Island Reservoir. Experiments and observations appear to demonstrate that no nuisance would be caused for years, if ever, by discharging continuously near Deer Island Beacon. The saving in interest alone by direct discharge would within twenty years pay the cost of a reservoir and an additional outlet. The cost of pumping and other items of expense will also be lessened by omitting a reservoir. It may also be noted that storing sewage for a few hours may give an offensive smell which it would not otherwise have.

If a reservoir shall be needed it will cost no more to build at a later time, and therefore, in any event, such building should be postponed until the effect of discharging the sewage continuously is clearly seen.

PUMPING ENGINES.

Two engines each, with boilers, piping, etc., are now being built for the proposed pumping stations at Deer Island, East Boston, and Charlestown. Regarding the plant for the first two stations: Each engine is to be capable of easily raising 70 cubic feet of sewage 19 feet vertically above the level of the sewage pump well and to raise to greater heights up to 25 feet quantities of sewage inversely proportional to such lifts. Each is also to be capable of pumping at as low a rate as 15 cubic feet per second and at all rates between 15 and 70 cubic feet per second. The pumps will be of the centrifugal type, with vertical shafts. The suction and discharge pipes will be each 48 inches in diameter and intended to run at speeds varying from sixty to one hundred revolutions per minute, according to the amount of sewage and the height to which it is lifted. The pump wheel is to be driven by a triple expansion engine of the Corliss type. The diam-

eter of the cylinders will be $13\frac{1}{2}''$, $24''$, and $34''$, with a $30''$ stroke. Condensers will be used. The discharge channels from the pumps will contain check valves to prevent any backward flow when the pumps are stopped. The inlet channels from the pump wells will be provided with gate valves to admit of closing off the passage when desirable.

The quantity of sewage arriving at the Charlestown Pumping Stations will be about half that at the East Boston or Deer Island Pumping Station. The engines will be similar in general design to those for East Boston and Deer Island. Each pump will have a capacity of 35 cubic feet per second raised 11 feet high. The suction and discharge openings will be $36''$ in diameter. The diameter of the pump wheels will be about 8 feet. The cylinders will be $10''$, $18''$, and $36''$, with a $30''$ stroke.

CONSTRUCTION.

A small portion of the work on the sewerage system has been shallow. In general, however, much deep and difficult excavation has occurred, requiring skill, ingenuity, and fertility in resources on the part of the engineers and contractors. In most of the excavation machinery of some kind has been employed, as, for instance, the boom derrick, the A frame, the incline, but it has been mostly done by trench machines.

Sections 1 (Deer Island Outlet), $3\frac{1}{2}$ (Shirley Gut Siphon), 10 (siphon under Chelsea River), 25 (siphon under Mystic River, Charlestown), and other parts involving much more than ordinary risk, and on which it might be necessary to change the plans during construction, have been or are now being done by foremen and laborers directly under the supervision of the engineering department instead of by contract. Some account of the work on two of these sections will now be given.

SECTION 25, MYSTIC RIVER SIPHON.

A sewer tunnel is now being built under Mystic River parallel with and about 58 feet from Malden Bridge, and when completed it will extend from Tuft's Mill Pond to the site of the Charlestown Pumping Station, a distance of about 862 feet. It has now nearly reached the pumping station. The bore of the tunnel before the brickwork is put in is about 7 feet in diameter. The average depth

of the bottom of the tunnel excavation below the floor of Malden Bridge is about 45 feet. The average thickness of the earth over the crown of the arch is about 15 feet. At some places it is only about 6 feet (Figure 1, after page 298). A shaft 49 feet deep is located at a point about 50 feet from Mystic River at the southerly end of Malden Bridge.

Large quantities of sulphureted hydrogen were encountered, so that the men were able to remain in it but for about an hour at a time. The annoyance from the sulphureted hydrogen was partially alleviated by forcing a volume of fresh air into the shaft by means of air compressors. About one in the morning of June 6 a pocket of carbonic acid gas was struck. The gas flowed into the trench and suffocated two men almost instantly and overcame a foreman who went to their assistance. The foreman was rescued, and recovered in a day or two.

After a trial of various measures which proved only partially remedial a vertical lock was put in the shaft, and the sinking finished by the use of compressed air. The shaft was down June 30 and the heading commenced. A horizontal air lock was put in the tunnel, and excavation under pressure began July 24. The roof of the tunnel is kept in place as digging progresses by steel flanged plates bolted together and supported temporarily by screw braces. These plates usually extend about one third of the way around the periphery of the tunnel bore Sometimes in treacherous earth they are made to extend much further. The tunnel invert is usually one foot in thickness. The arch varies from 1 foot to 2 feet in thickness and averages about 1 foot 3 inches. The material excavated in tunneling has been mainly in clay, but partly of sand. During the progress of this work bubbles of air have been seen to freely escape from the water above the tunnel. On the last day of October the agitation near the end of the tunnel as then excavated was more violent than usual, and two compressors were required to keep up the pressure. The men stopped work at midnight and went outside to eat. On their return the leak was found to be greater than before. They made some effort to stop it, but as the leak was increasing at a dangerous rate were forced to retreat a distance of more than six hundred feet to the interior of the air lock and close its door. The water was then knee deep in the tunnel and lock and rising fast. Ten minutes thereafter the tunnel was filled with mud and water. Fortunately no lives

were lost. The next day soundings revealed a crater-shaped hole near the end of the tunnel. Repairs were begun by filling the hole with clay. A canvas sail was obtained and weighted on one side. It was sunk in such a manner that the current caused the canvas to spread over the clay-filled hole. The canvas was then covered with clay. The tunnel was soon afterwards pumped out, and progress has since been uninterrupted.

SECTION $3\frac{1}{2}$, SHIRLEY GUT SIPHON.

Shirley Gut is the name given to a narrow strait which separates Deer Island from Winthrop. At the point selected for the sewer crossing it is about 315 feet wide at mean high water and has a width of about 105 feet at low water. The tidal current, which is noted for its swiftness at this point, practically never ceases. The depth of water at mean high tide in the middle of the Gut is about 25 feet. The shores and bed consist of gravel and sand down to respective depths on the Deer Island and Point Shirley sides of about 26 and 66 feet below mean low water, where clay is found.

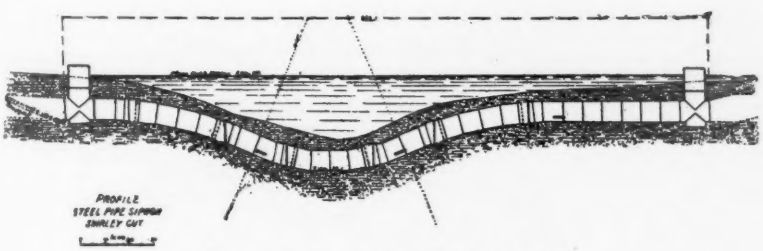


FIG 2. PROFILE OF SHIRLEY GUT SIPHON.

It was necessary that the sewer passing under the Gut (connecting the sewer already laid on the Winthrop side with that on the Deer Island side) should be in the shape of a depressed curve (Figure 2) or inverted siphon, having its axis in the middle of the Gut about 22 feet lower than the axis of the sewer on the Winthrop side.

This was necessary in order not to impair navigation, and it involved digging a trench beneath from 12 to 18 feet below its bed. Various methods of construction had been suggested. The best of all, so far as the sewer is concerned, would have been to make a permanent causeway across and build the sewer with a straight grade, and

thus dispense with the siphon. This was at one time considered by the board. A hearing was had on the subject, but, as considerable opposition was met, it was thought that seeking the necessary Congressional and State legislation would involve too much delay, with considerable chance of its being rejected.

A practicable method would have been to descend in a shaft about 70 feet on the Winthrop side into the clay, tunnel under the Gut in this clay, and ascend on the Deer Island side. It has been constantly kept in view in designing all parts of the Metropolitan System to so place the sewer as to admit of its examination with little difficulty at any time. The objection to the method of deep tunneling just referred to is that its great depth would make it slow and expensive work pumping out the siphon for examination.

It was concluded, on the whole, that it would be better for all concerned that the State should incur the risks of the work. It was therefore done directly under the direction of the engineering department.

After a careful study and consideration of the various questions involved it was concluded that a single line of pipe having the same capacity as a double line previously proposed would be simpler and more reliable in management when the works were in actual use, although it might possibly be more costly in first construction. This led to the plan of a line of sewer across the Gut formed of masonry 12 inches in thickness surrounded by a shell of steel three eighths of an inch in thickness. The use of the steel shell was for strength and tightness in the process of laying. It was not necessary that it should prove permanent. A branch was to be provided at each side of the Gut so that, should experience in actual maintenance and operation of the system show it to be desirable, an additional line could be laid across in the future when found to be necessary.

It was at first proposed to lay the steel pipe in the trench in sections of 50 or 60 feet, employ a diver to connect the sections, then pump out the interior and lay the 12-inch shell of brickwork therein. With the pressure of water that would exist under these conditions steel shells far thicker than those proposed would collapse before the water could be pumped out. To prevent this it was proposed that the pipes should be braced interiorly with closely placed wooden-braced rings, to be placed in the pipes before they were moved from the shore. Further consideration led to making use of the brick-

FIGURE 3. CENTER SECTION, SHIRLEY GUT SIPHON.

work itself for bracing the pipes, although their weight would then be increased sixfold.

The first step in carrying out this design was to build across the Gut a bulkhead whose maximum height was about 27.5 feet, with a length of about 467 feet, and with its top about 12.7 feet above mean low water. This bulkhead or dam was built of sufficient strength to resist the pressure of the tidal current and to successfully withstand many storms that have since occurred. This dam stopped the swift tidal current and enabled a dredge to operate. The trench dredged in this comparatively still water stood fairly well. The heavy storms of August partially filled it, and considerable redredging was done.

The steel pipes, in sections of 48 to 68 feet, were placed near high-water mark on the Winthrop shore. They were lined with brickwork about 13 inches thick and bulkheads were constructed at the end of each section. These bulkheads were 8 inches thick, of hard pine timber, and were calked and pitched by ship calkers. As a further precaution they were covered with sheets of rubber, which were cemented to the steel outer skins of the sections. The bulkheads were strongly secured to the masonry of the pipes. To test the tightness of these pipes an attempt was made to exhaust the air from the interior of them by means of small steam ejectors. After several hours it was found that the partial vacuum, as indicated by an ordinary vacuum gauge, was only about one inch of mercury. The rubber sheets were then taken from the ends of the pipe and the ends covered with Portland cement mortar. This mortar after it was set was painted with asphalt, and various joints of the steel structure were examined and leaks found and stopped and the pipes made practically tight. Figure 3 shows the center section in process of construction.

On the afternoon ebb tide of September 13 and the morning ebb of the 14th the middle section was moved on rollers to low-water mark by building movers, Cavanagh and Sons.

In the mean time the dredging scow, 33 feet 8 inches wide, 79 feet long, and 6 feet 6 inches deep, had been fitted with two overhanging trestles or shears, with specially made blocks and tackle for hoisting, holding, and lowering the pipe. These shears were placed on the side of the dredge about 35 feet apart, and so arranged that they could be later moved to other appropriate distances for handling the following pipes. About 12.30 o'clock P.M., on September 14, the tide then lacking about one hour from high water, the dredge was anchored to

the southward and the hoisting tackles were attached to steel straps toward the two ends of the pipe. The four drums of the two hoisting engines were then slowly set winding. In this manner the pipe was partly lifted and partly pulled from the 12-inch square timbers and

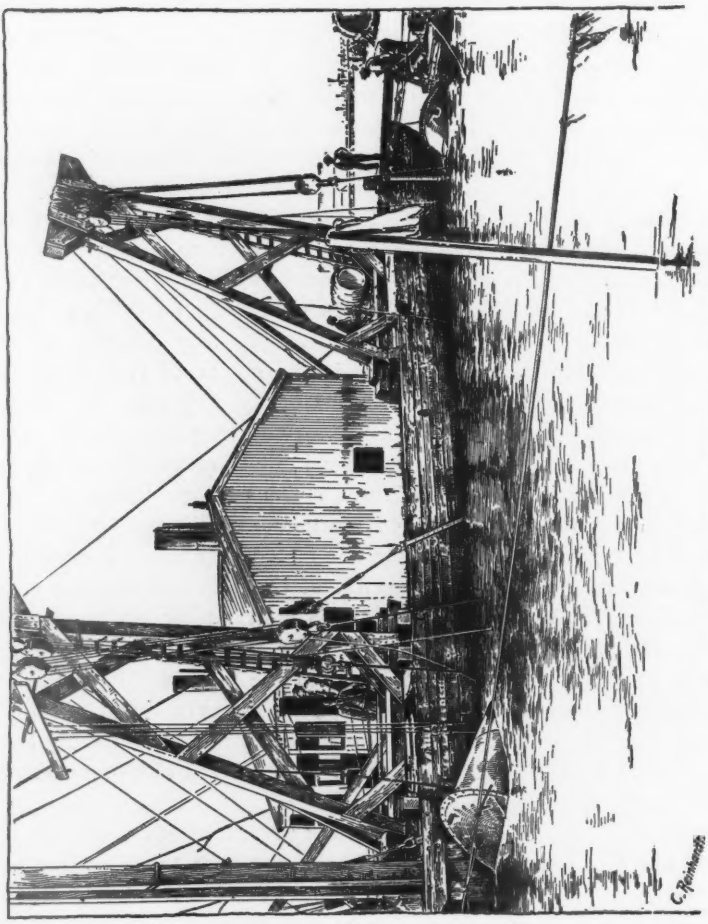


FIG. 4. CENTER SECTION READY TO BE LOWERED.

about eighty hard wood rollers on which it rested. The rollers and blocking immediately rose to the surface, covering the vicinity with floating wood. The dredge and the pipe were then pulled out to deeper water and the pipe slightly lowered. It was found that the

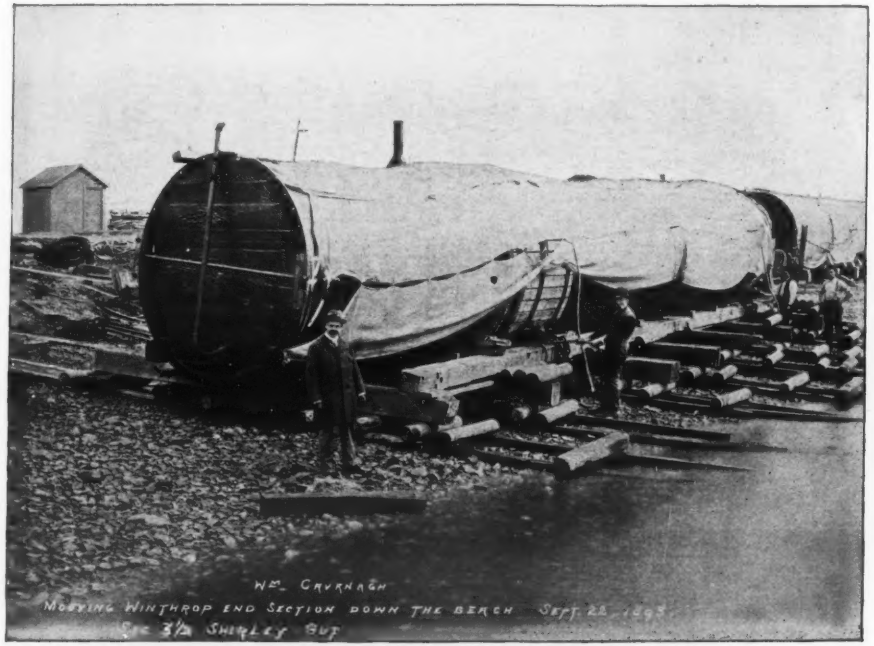


FIGURE 5. MOVING WINTHROP END SECTION, SHIRLEY GUT SIPHON.

weight of the pipe in salt water was just about equal to the displacement and when lowered it sank nearly but not quite to submersion. The weight in air of this pipe was about 225,000 pounds.

The scow and pipe were then moved so that the latter was nearly over the position which it was finally to occupy. As has been seen by the profile, the pipe was bow-shaped, and when moved from the shore to near its final position its symmetrical plane was horizontal. The pipe had now to be revolved ninety degrees, so that its symmetrical plane would become vertical with the concave side of the pipe uppermost (Figure 4). This was done by hoisting on two ends of the

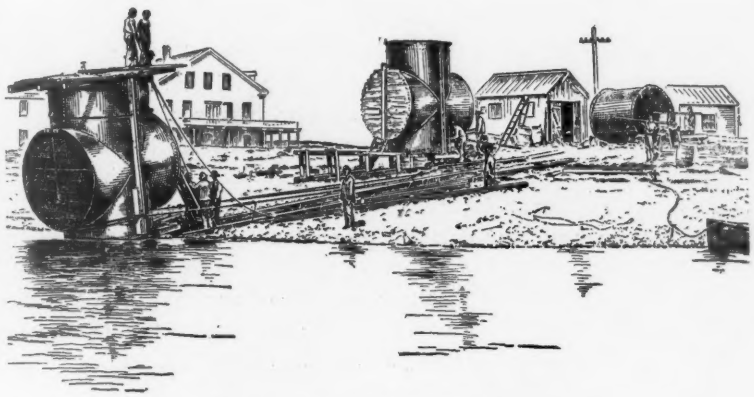


FIG. 6. MANHOLE SECTIONS ON BEACH.

straps and lowering on the other two ends. After letting some water into the pipe through a small gate and increasing its weight with a few sand bags it was lowered to its final position and rested on two accurately placed cross sills provided for that purpose. Its true position in plan as it was lowered was determined by vertical wires which were stretched from points on the middle plane of the pipe to pulleys on the hoisting rig. Its descent to its true position in plan was facilitated and partly brought about by two ropes, one at each end of the pipe. These ropes passed under pulleys anchored in the bottom of the Gut in the exact central line of the sewer. The ropes ascended

to the top, were led to the scow, and were kept in tension by six or eight men to each rope.

The other three long pipes were on following days successfully moved down the beach (Figure 5), carried out into the Gut, partially revolved, lowered to the bottom, and bolted one to another. This latter work was done by divers.

Many details were provided to compel each pipe, though under water and out of sight, to go precisely to its proper place and to give evidence above the surface that this was being accomplished. All these devices resulted in reducing the work of the divers to the lowest practicable terms.

Figure 6 shows one of the short manhole sections as it is being moved down the beach, and Figure 7 shows it on its way from the beach to its position in the siphon.

The interior bulkheads have now all been removed from the siphon, and the short spaces between the pipes at the joints formerly occupied by the bulkheads have been filled with masonry. The pipes were found to be tight and in an exceedingly satisfactory condition.

The various assistants and foremen connected with the Shirley Gut Siphon took great interest in thinking out and discussing with the writer the necessary details, and our success was largely due to their intelligent work.

It can be said further that any measure of success which may be achieved on the system as a whole will be largely due to the earnest and intelligent work of the engineering and other assistants.

FIGURE 7. MANHOLE SECTION, FLOATING, SHIRLEY GUT SIPHON.

SOME EXPERIMENTS FOR DETERMINING THE REFRACTORINESS OF FIRE-CLAYS.[1]

By H. O. HOFMAN and C. D. DEMOND.

Received December 18, 1893.

There are two methods of determining the fusibility or refractoriness of fire-clays, the theoretical and the experimental. In the former, conclusions are drawn from the chemical composition; in the latter, from the changes which the clay undergoes when subjected to intense heat. It is well to use both methods, beginning with the actual heat-test and explaining the results obtained from this by the help of the chemical analysis. In discussing the subject, however, it is better to reverse this order.

I. The Theoretical Method.[2]

Leaving out the hygroscopic and combined waters and any organic matter, as not directly affecting the fire-resisting property, the refractory constituents of fire-clay are alumina and silica, and the fluxing constituents magnesia, lime, soda, potash, and ferric oxide. According to Bischof,[3] alumina is the least fusible component, and silica follows close upon it. If, however, a mixture of the two be heated, it will be found that its melting point is much lower than that of alumina, as a silicate will then have been formed. The way in which silica affects the refractoriness of alumina has been strikingly presented by Seger[4] in a diagram reproduced in Figure 1. The abscissæ represent the melting points of Seger cones Nos. 26 to 36; the ordi-

[1] Read at the Virginia Beach Meeting of the American Institute of Mining Engineers, February, 1894.

[2] C. Bischof, Die feuerfesten Thone, Leipsic, 1876, p. 71.

R. Keller (Revised by C. Bischof), Ueber die Fabrication und Anwendung feuerfester Steine, Aix-la-Chapelle, 1890; a lecture, pp. 1–16.

Bruno Kerl, Handbuch der gesammten Thonwaarenindustrie, Brunswick, 1879, pp. 59 and 71.

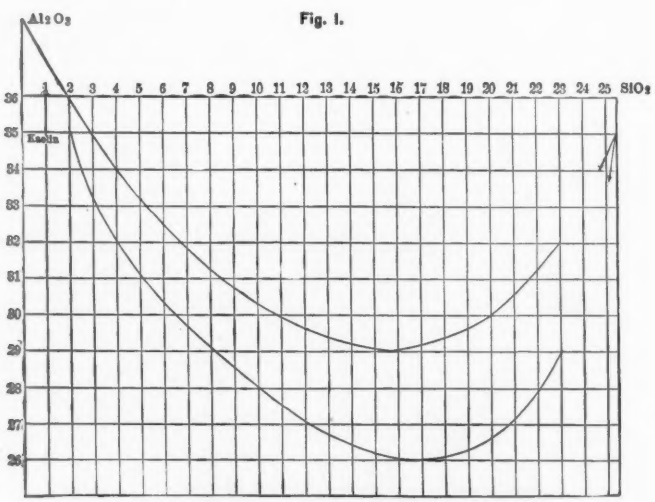
J. Post, Chemisch-technische Analyse, Brunswick, 1890–91, Vol. II, p. 48.

[3] Dinglers Polyt. Jour., Vol. CLXIX., pp. 353, 455; Vol. CLXX., p. 43.

[4] Thonindustrie-Zeitung, 1893, p. 391.

nates, the relative amounts of alumina and silica in the mixture. The least fusible consists of one molecule of alumina and two molecules of silica, and melts, as shown by the upper curve, at a temperature indicated by Seger cone No. 36. The fusibility is seen to increase with the amount of silica up to the proportion $1Al_2O_3 : 17SiO_2$, and then to decrease (on account of the preponderance of silica, which cannot combine to form a silicate), until, finally, the effect of the alumina has disappeared and the melting point of silica, equal to that of Seger cone No. 35, has been reached. The lower curve shows in a similar way the effect of silica on the fusibility of the kaolin from Zettlitz, Bohemia (see Table I, page 304). The practical deduction is that the refractoriness of a fire-clay increases with the amount of alumina it contains.

Fig. 1.



FUSIBILITY OF ALUMINA-SILICA AND KAOLIN-SILICA MIXTURES.

The effects of the fluxing constituents have been studied by Bischof[1] and Richters.[2] The latter, in 1868, propounded the law that their fluxing property is inversely proportional to their molecular weights; thus, 40 magnesia would have a slagging effect equivalent to that of 56 lime, 62 soda, 94 potash or 160 ferric oxide. While Bis-

[1] Dinglers Polyt. Jour., Vol. CLXV, p. 378; Vol. CXCVI, pp. 438, 525; Vol. CXCVIII, p. 407. Thonindustrie-Zeitung, 1885, p. 13.

[2] Dinglers Polyt. Jour., Vol. CXCI, pp. 59, 150, 229; Vol. CXCVII, p. 268.

chof[1] supports this view to-day, it is attacked by Seger,[2] who maintains that ferric oxide has a stronger slagging effect than any other of the four bases. Whatever may be the precise order in which these bases are to be placed, one thing is settled, namely, that if their total amount exceeds 6 per cent. of the ignited clay, this cannot be classed any longer as refractory.

To sum up, the fire-resisting power of a clay, considered from a chemical point of view, depends first upon the character of the fluxing constituents and their relation to alumina and silica, and, secondly, on the relation of alumina and silica to one another. Bischof[3] arrives at the refractory character of a clay by what he calls the refractory quotient, which he obtains by dividing the quotient of the oxygen of the fluxes into that of the alumina by the quotient of the oxygen of the alumina into that of the silica.[4]

In the seven standard fire-clays which he selected as types (see Table I, which has been slightly changed from the original) this refractory quotient is 13.95 with the most refractory clay — No. 1, from Saarau, Silesia — and decreases with the fire-resisting power until it reaches in clay No. 7, from Niederpleis, Nassau, the figure 1.64, and a clay the refractory quotient of which is less than 1 (equal to Seger cone No. 26) is not to be classed any longer as refractory. Taking as an example clay No. 2 of Table I — the kaolin from Zettlitz, Bohemia — the refractory quotient would be

$$\text{R. Q. B.} = \frac{\text{O in } Al_2O_3}{\text{O in RO}} \div \frac{\text{O in } SiO_2}{\text{O in } Al_2O_3} = \frac{17.960}{1.401} \div \frac{24.363}{17.960} = \frac{12.82}{1.35} = 9.49.$$

[1] See Keller-Bischof, op. cit., p. 7.

[2] Thonindustrie-Zeitung, 1893, p. 392.

[3] Dinglers Polyt. Jour., Vol. CXCIV, p. 420; Vol. CXCVI, pp. 438, 447, 525; Vol. CC, pp. 110, 289. Thonindustrie-Zeitung, 1888, pp. 38, 50.

[4] When Bischof made his researches silica was written SiO_3. The quotient, expressed as above, would have had the form $\frac{\text{O in } Al_2O_3}{\text{O in RO}} \div \frac{\text{O in } SiO_3}{\text{O in } Al_2O_3}$, and in carrying out any calculations the oxygen of RO would have to be multiplied by three. For Seger's refractory quotient (see later) the ratio $\frac{\text{O in } SiO_3}{\text{O in RO}}$ is required; here also the oxygen of RO has to be multiplied by three. To-day the old mode of expressing the value is retained and the new atomic weights are adopted.

To find the oxygen in the components of clay each is multiplied by its coefficient, as $Al_2O_3 \times 0.466$, $SiO_2 \times 0.533$, $MgO \times 0.400$, $CaO \times 0.2857$, $K_2O \times 0.1698$, $FeO \times 0.222$.

Iron, present in the clay usually as ferric oxide, is figured as ferrous oxide, $Fe_2O_3 \times 0.9 = 2FeO$. Soda is figured as potassa, $62Na_2O$ being equivalent to $94K_2O$.

$$\frac{\text{O in } Al_2O_3}{\text{O in RO}} \div \frac{\text{O in } SiO_2}{\text{O in } Al_2O_3}.$$

TABLE I.—BISCHOF'S STANDARD FIRE-CLAYS.

Fire-Clay.		Al_2O_3.		SiO_2.			RO.						
Name and Source.	No.	Total per cent.	Oxygen per cent.	Combined per cent.	Non-combined per cent.	Total per cent.	Oxygen per cent.	MgO per cent.	CaO per cent.	K_2O per cent.	Fe_2O_3 per cent.	Total per cent.	Oxygen per cent.
Saarau, Silesia	I.	36.30	16.917	38.94	4.90	43.84	23.366	0.19	0 19	0.42	0.46	1.26	0.293
Zettlitz, Bohemia	II.	38.54	17.960	40.53	5.15	45.68	24.363	0.38	0.08	0.66	0.90	2.02	0.467
Andennes, Belgium	III.	34.78	16.208	39.69	9.95	49.64	26.457	0.41	0.68	0.41	1.80	3.30	0.778
Coblence, Rhen. Province . .	IV.	36.00	16.777	41.00	6.74	47.74	25.445	0.33	0.40	1.05	2 57	4.35	0.938
Grünstädt, Palatinate	V.	35.05	16.334	39.32	8.01	47.33	25.225	1.11	0.16	3.18	2 30	6.75	1 490
Cassel, Hesse	VI.	27.97	13.035	33.59	24.40	57.99	30.908	0.54	0.97	0.53	2.01	4.05	0.985
Niederpleis, Nassau	VII.	28.05	13.072	30.71	27.61	58.32	31.084	0.75	0.72	1.39	1.89	4.75	1.120

TABLE I. — *Concluded.*

Fire-Clays.		Loss by ignition, per cent.	O in Al_2O_3 divided by 3O in RO.	O in SiO_2 divided by 3O in RO.	O in SiO_2 divided by O in Al_2O_3.	Pyrometric Equation.	Refractory Quotient.		Relative Refractoriness.	Corresponding Seger Cone.
Name and Source.	No.						Bischof R. Q. B.	Seger R. Q. S.		
Saarau, Silesia	I.	17.78	19.25	26.50	1.38	$19.25(Al_2O_3, 1.38SiO_2) + RO$	13.95	33.15	100	36
Zettlitz, Bohemia . . .	II.	13.00	12.82	17.31	1.35	$12.82(Al_2O_3, 1.35SiO_2) + RO$	9.49	22.31	60–70	35
Andennes, Belgium . . .	III.	12.00	6.86	11.20	1.63	$6.86(Al_2O_3, 1.63SiO_2) + RO$	4.21	11.08	50	33
Coblence, Rhen. Province,	IV.	11.81	5.96	9.10	1.51	$5.96(Al_2O_3, 1.51SiO_2) + RO$	3.95	9.97	45	32
Grünstädt, Palatinate . .	V.	10.51	3.65	5.64	1.54	$3.65(Al_2O_3, 1.54SiO_2) + RO$	2.37	6.03	30	30
Cassel, Hesse	VI.	9.43	4.41	10.46	2.37	$4.41(Al_2O_3, 2.37SiO_2) + RO$	1.86	6.27	20	28
Niederpleis, Nassau . .	VII.	8.66	3.89	9.25	2.37	$3.89(Al_2O_3, 2.37SiO_2) + RO$	1.64	5.54	10	26

These figures embodied in Bischof's pyrometric formula for clay give

$$12.82\ (Al_2O_3,\ 1.35\ SiO_2) + 1\ RO.$$

Bischof's method has found pretty general acceptance within the necessary limitations. It is, however, questioned to some extent by Seger,[1] who says that while the refractoriness of a clay increases with the alumina and decreases with the silica, the proof is wanting that the decrease in refractoriness takes place in direct proportion to the amount of silica and the increase in proportion to the square of the alumina, and that, furthermore, the refractoriness does not depend solely upon the relation which silica and alumina bear to one another. He therefore recommends adding the ratio of fluxing constituent to alumina and that of fluxing constituent to silica, and multiplying this sum by the quotient obtained from dividing the latter into the former, thus:

$$\left(\frac{O \text{ in } Al_2O_3}{O \text{ in } RO} + \frac{O \text{ in } SiO_2}{O \text{ in } RO}\right) \times \left(\frac{O \text{ in } Al_2O_3}{O \text{ in } RO} \div \frac{O \text{ in } SiO_2}{O \text{ in } RO}\right).$$

Taking the same Zettlitz clay as example, Seger's refractory quotient would be:

$$\text{R. Q. S.} = (12.82 + 17.31)\ \frac{12.82}{17.31} = \frac{30.13}{1.35} = 22.31.$$

Bischof[2] does not consider Seger's refractory quotient an improvement on his own, and suggests that the older quotient be maintained until something better shall be discovered. Both quotients are used, Bischof's, however, being the more common one. In comparing the two by the standard clays (Table I), it will be seen that while the experimental results of both Bischof (relative refractoriness) and Seger (number of corresponding cone) agree with Bischof's refractory quotient, there is a discrepancy with Clay VI, which Seger's refractory quotient would make more refractory than Clay V. Something similar is to be noted in Table III, where Seger's refractory quotient makes the kaolin from Blanford, Massachusetts, less refractory than the clay from Mount Savage, Maryland, while the experiments of Tables IV and V prove the contrary to be the case. In the single series of experiments in Tables IV, V, and VI, both refractory quotients increase, on the whole, with the refractory values of the mixtures, but it has not

[1] Thonindustrie-Zeitung, 1877, pp. 290, 296; 1889, p. 332; 1893, p. 339.
[2] Thonindustrie-Zeitung, 1889, p. 331.

been possible to find the desirable regularity which was thought to exist. Nevertheless, the quotients have been embodied in the tables in order to furnish another means of judging of the refractory character of the clays and their mixtures made for experiment.

No deduction, however, made from the chemical analysis can have the force of a positive determination, because analysis necessarily ignores the physical constitution, whereas a coarse-grained clay is less fusible than a fine-grained, and a compact[1] than a loose one. Moreover, a clay is not one chemical compound, but an intimate mechanical mixture of several minerals. The more impurities a clay contains (quartz, feldspar, mica, etc.), the more liable will these be to combine upon heating to a fusible compound and attack the practically infusible clay substance (kaolinite). The result of the chemical analysis will therefore be the more applicable the purer the clay, but in any case will only have an approximate value, and must be supplemented by actual experiment.

II. — The Experimental Method.[2]

A. *Introductory.*

Experimental methods may be classified as direct and indirect. Until lately all the direct methods have given only what may be called qualitative results, *i.e.*, small samples of clay have been exposed to an elevated temperature and the effect has been noted, whether as a complete fusion or only as a fritting, or whether the clay remains unaltered. Examples of this method are the tests of Knafft, Bischof, and Otto. Knafft[3] exposes the end of a small pointed cone of clay for a short time to the hottest part of the flame of a blowpipe with the result that the point remains unaltered or becomes rounded off or fused. Bischof prefers to expose the clay to the flame in the loop of a platinum wire. He obtains it in a suitable form by coating a piece of oiled paper with a thin paste of the clay and water and then drying, when the clay peels off in small thin tablets. Another of his qualitative tests[4] is to place a small sample of dry pulverulent clay in a crucible and heat it in a furnace with forced draught for two hours

[1] Bischof, Thonindustrie-Zeitung 1886, p. 430; Seger, ibid., 1890, p. 201.
[2] Bischof, op. cit., p. 92; Kerl, op. cit., p. 62; Post, op. cit., p. 50.
[3] Dinglers Polyt. Jour., Vol. CLXXIV, p. 292.
[4] Op. cit., p. 93.

or more. The clay will remain unchanged, or will be fritted or fused according to the degree of refractoriness. His effective tests to distinguish fritting from fusing are to draw a line with pen and ink over the fracture of the sample or touch it with the tongue. If it is fritted it will adhere, and the ink will spread as it would on blotting-paper; if it is fused it will not stick to the tongue, and the pen and ink line will be sharp and clear. The transition from qualitative to quantitative work is made by Otto,[1] who forms two small test-bricks ($4\frac{3}{4}$ by $2\frac{3}{4}$ by $1\frac{3}{4}$ inches) from a uniform mixture of half-raw and half-burnt clay, places them alternately with two other bricks of the same size and of known properties to form an oblong on a refractory pedestal in a crucible furnace, and then heats them with charcoal, coke, and forced draught for about two hours. A comparison of the four samples shows if the heat was uniform, and how the test bricks compare with the standards. The only quantitative direct method is that by Seger and Cramer,[2] who form from the sample of clay to be tested a number of cones of the same size as Seger's small-sized standard cones, Nos. 26 to 36, inclose a test-cone with two different numbers of the standard cones in a magnesia crucible, and heat with gas-carbon in a Deville furnace lined with chromite. This is repeated with fresh cones and different temperatures until the place of the test-cone in the series of standards has been found. It is proposed to make at an early date an extended series of tests by this method, and further discussion of it will therefore be postponed for the present.

The indirect methods all have the common characteristic of mixing the clay that is to be tested with fluxing or refractory substances until it shows the same behavior in the fire as a given standard clay. The amount of ingredient required to accomplish this will be the measure of the fire-resisting value. All the tests so far have been made in clay crucibles, placed in a Sefström or Deville furnace, the fuel used being coke, or, preferably, gas-carbon, and the temperatures aimed at varying from 1500° to 1775° C. Bischof, who originated these methods, first used the one known as the quartz method,[3] in which he toned down refractory clays by the use of finely pulverized quartz or chemically pure silica. The manner in which silica acts on alumina and clay (kaolin) has been shown in Figure 1. Bischof was followed by Rich-

[1] Dinglers Polyt. Jour., Vol. CLXIII, p. 193; Thonindustrie-Zeitung, 1888, p. 163.
[2] Thonindustrie-Zeitung, 1891, pp. 195; 1892, pp. 675, 747; 1893, p. 339.
[3] Dinglers Polyt. Jour., Vol. CLIX, p. 54; Vol. CLXI, pp. 208, 291.

ters, who devised the supplementary alumina method,[1] which tones up a low-grade clay with pure alumina until it shows the same behavior in the fire as the standard, together with which it is heated. The disadvantages of these methods, namely, the excessive nicety required in regulating the high temperatures with the silica method, and the tendency of the reagent in the alumina method to act too powerfully, and also the fact that the silica method is not always applicable, prompted Bischof to combine the two in his silica-alumina method,[2] in which he uses as ingredient an intimate mixture of equal parts of chemically pure silica and alumina. This does not soften at the highest temperatures, and as it is more refractory than the best clay known, it will always tone up any clay to which it is added. The mode of procedure is to weigh out ten samples of 0.1 gramme each of clay that has been ground and ignited, to mix them severally with 0.1, 0.2, 0.3, etc., grammes of the ingredient, and form prisms $\frac{1}{4}$ inch high and $\frac{5}{32}$ inch square. These are inclosed in crucibles ($1\frac{3}{4}$ inches high, $1\frac{1}{2}$ inches in diameter at the top and $\frac{3}{4}$ inch at the base, with walls $\frac{3}{16}$ inch in thickness), three or four in each, with a prism of the standard consisting of equal parts of Saarau clay (see Table I), and the ingredient, and the value of which is assumed as 100. The crucibles are placed in a Deville furnace and heated to the melting point of wrought iron (say 1600° C.). The prism, which shows the same behavior in the fire as the standard, is the critical mixture. An arithmetical expression for the refractoriness is obtained by multiplying the amount of ingredient it contains by 100, and deducting the product from the value of the standard. Thus, if 0.1 gramme test-clay required 0.5 grammes of ingredient, its refractory value would be:

$$100 - 0.5 \times 100 = 50.$$

In this manner the relative refractoriness of the seven standard clays in Table I was determined by Bischof.

B. *New Experiments.*

1. *Introductory.* — Hitherto experiments with fire-clays have always been carried on in crucibles and with extremely high temperatures. The sample has necessarily been excluded from view during the opera-

[1] Ibid., Vol. CXCI, pp. 59, 150, 229; Vol. CXCVII, p. 268.

[2] Dinglers Polyt. Jour., Vol. CXCVI, pp. 438, 525; Vol. CXCVIII, p. 396.

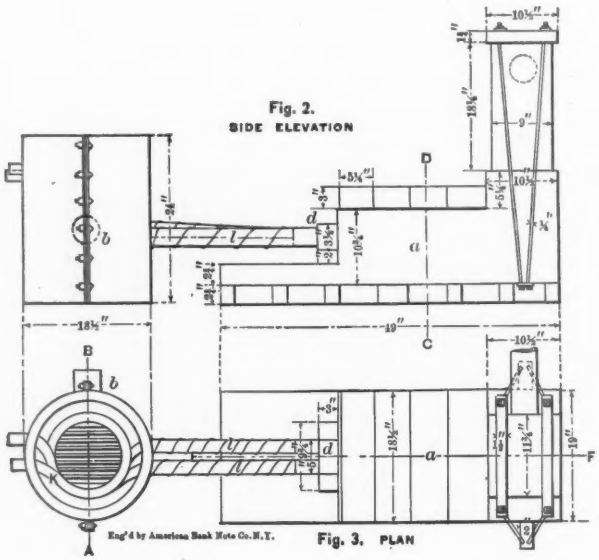


Fig. 2.
SIDE ELEVATION
Fig. 3. PLAN
Engʼd by American Bank Note Co. N.Y.

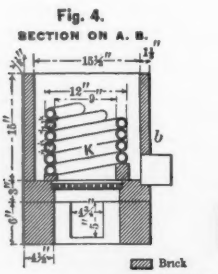


Fig. 4.
SECTION ON A. B.
Brick
Slag Wool

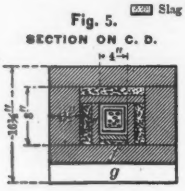


Fig. 5.
SECTION ON C. D.

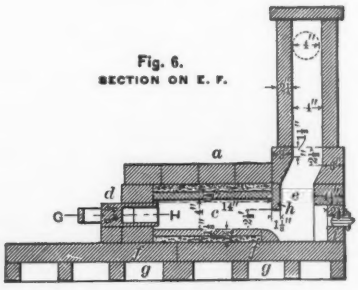


Fig. 6.
SECTION ON E. F.

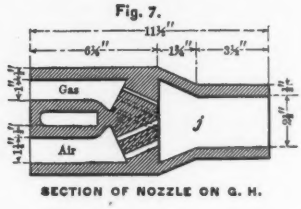


Fig. 7.
Gas
Air
SECTION OF NOZZLE ON G. H.

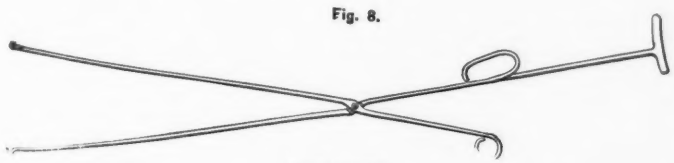
tion, and the changes could only be observed after the crucible had been taken from the fire and sufficiently cooled to allow an examination of its contents. The temperature of a small crucible-furnace using solid fuel and blast could not be controlled with any degree of nicety, and the measurement of changes of temperature in the crucible, if not impossible, was at least not satisfactory. The writers have therefore attempted:

(*a*) To construct a furnace in which the temperatures could be easily measured and controlled, and the samples watched while the tests were being made, and taken out or exchanged with little or no delay.

(*b*) To devise a method of testing which did not require temperatures approximating to or surpassing the melting point of platinum, or 1775° C.

2. *The Furnace.* — Figures 2 to 7 represent the form of furnace finally adopted after a series of preliminary experiments. In it all the

Fig. 8.



CONE-TONGS.

work here to be described was carried out. It consists of two parts, the furnace proper, *a*, and the heating stove, *b*. The furnace is built on the same principle as the one used by Dr. W. W. Jacques, physicist of the Bell Telephone Company for high temperature work. It consists of a rectangular combustion chamber, *c*, having a nozzle, *d*, at one end for the supply of gas and air, and a well-braced vertical chimney, *e*, at the other to carry off the products of combustion. The chamber is inclosed with thin fire-bricks (Figures 5 and 6), which are surrounded by slag-wool to reduce the loss of heat by radiation. It rests on two tiles; the side walls are of ordinary fire-brick laid in clay, and the roof is of four tiles laid dry. At the flue-end of the chamber there is a curtain-brick, *h*, which deflects the flame away from the roof, and thus produces a more uniform temperature than would otherwise be possible.[1] At the foot of the chimney is the working-door, $4\frac{1}{2}$ by

[1] This might perhaps be done in a simpler way by drawing the products of combustion downward instead of upward.

5 inches, through which the samples of clay to be tested are introduced with a long pair of tongs (Figure 8, one arm 45 inches, the other 34 inches), which have proved very serviceable. The working-door is closed with a fire-brick, *i*, having a peep-hole in the center, through which a pyrometer can be inserted. It is usually closed with a clay plug. The nozzle, *d*, drawn to a larger scale in Figure 7, is so constructed that gas and air coming into the chamber, *j*, obliquely to one another in a number of small streams are intimately mixed before they issue forth into the furnace, and this insures a very satisfactory combustion. The chamber soon becomes dazzling white. To enable the nozzle to resist this intense heat, it is made of suitable proportions of raw and burnt clay, alumina and asbestos; it is air-dried for several weeks and then placed in the furnace without previous baking. The stove (*b*, Figures 2, 3, etc.), in which air and gas are heated before they come together in the nozzle, was proposed by Prof. R. H. Richards. It consists of a sheet-iron cylinder lined with fire-clay and closed at the top with a sheet-iron cover ($\frac{1}{8}$ inch thick, not shown in the drawing) having two peep-holes. Above the ash pits is a circular cast-iron grate on which rest the two heating-coils, *k*, made of wrought-iron pipe wound together. The hot gases from the charcoal fire maintained on the grate pass up inside the coils, down on the outside, and then off through the flue, which is at the level of the grate. Thus the coils are heated outside as well as inside. Two pieces of wrought-iron pipe, *l*, inclosed in slag-wool, which is held in place by asbestos-paper and wire, are screwed on to the protruding ends of the heating coils; they abut against the clay nozzles, the joints being made air-tight with a luting of clay and slag-wool. This furnace, like every other, shows a difference of temperature between the places where the flame enters and those where it leaves the chamber. The first step was to settle the distances from the nozzle within which the temperature was uniform. The observations made with the Le Chatelier pyrometer are given in Table II. They show a uniform temperature in the space between $4\frac{1}{2}$ and 10 inches from the nozzle. These measurements were made along the bottom of the furnace, when it was 4 inches wide and 6 inches high, and the layer of slag-wool on the bottom and the deflecting curtain had not yet been added. Hence the roof of the furnace showed at that time a higher temperature than the floor. The highest temperature attained in the furnace was 1720° C., at about 3 inches from the floor and $4\frac{1}{2}$ inches from the

nozzle. A still higher temperature was expected, as in a larger furnace of similar construction, not having any provision for reducing the loss of heat by radiation, platinum had been melted in two hours after starting, the gas entering the heater through a $\frac{5}{8}$-inch pipe connected directly with a 3-inch main. The reason for the failure is the lack of gas, for, although a $\frac{5}{8}$-inch pipe is used, it passes through long and tortuous passages to reach the main. The temperatures attained were, however, more than sufficient for the tests.

TABLE II. — MEASUREMENTS OF TEMPERATURE IN FURNACE.

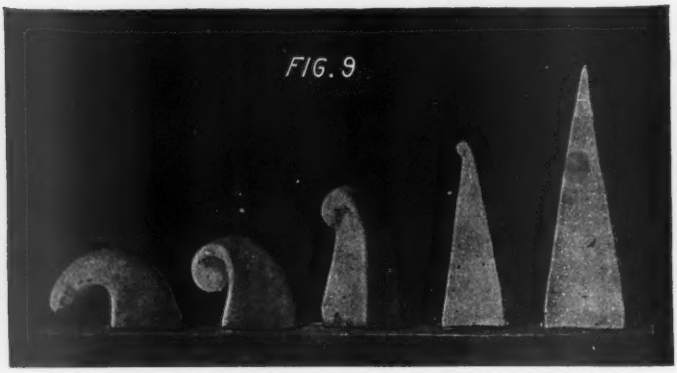
Distance from Nozzle. Inches.	Degrees centigrade.			
$1\frac{1}{2}$	1280	1395	....	....
$4\frac{1}{2}$	....	1420	....	....
$5\frac{1}{2}$	....	....	1360	1420
$7\frac{1}{2}$	1280	1430	....	....
$8\frac{1}{2}$	....	....	1370	1425
$10\frac{1}{2}$	1335	1420	....	....
$11\frac{1}{2}$	....	....	1355	1390
$13\frac{1}{2}$	1330	1345	....	....
$14\frac{1}{2}$	....	....	1210	1230

3. *The Standard of Measurement.* — Before entering upon the experiments proper, it was necessary to settle upon the standard by which any results were to be measured. Bischof's standard clays could not be taken, as the character of the deposits from which he received his material has changed, and samples of the old clays are not in the market. To overcome this difficulty, Seger got up his three-sided pyramids, going by the name of "Seger Cones." They are made with varying proportions of feldspar, kaolin, alumina, marble, quartz, and ferric oxide. The first set,[1] $\frac{3}{4}$ inch at base and $2\frac{3}{8}$ inches in height, contains twenty pieces, the respective numbers, Nos. 1 to 20, being impressed on them. They are intended to measure temperatures varying from 1150° C. to 1700° C., the difference between each cone

[1] Thonindustrie-Zeitung, 1886, pp. 135, 145, 168, 229.

and its neighbor being calculated as 28.9° C. The temperature indicated by the cone is supposed to be reached when its apex has bent down to the base.

Figure 9 presents a series of five cones, four of which illustrate the different stages of fusion, while the fifth (the largest, which has not been in the fire) shows how considerable is the shrinkage that takes place upon heating. A second set of cones of the same size, Nos. 21 to 25, and a third one of smaller proportions, Nos. 26 to 36,[1] melting at a gradually increasing temperature, No. 36 having the composition Al_2O_3, 2 SiO_2, complete the row in the ascending temperature scale. Last year a new set of ten cones of the large size was



brought out by Cramer.[2] They are marked 010, 09, ... 01, 1, and are intended to measure temperatures ranging from 960° C. to 1150° C., the difference of temperature indicated by each interval being 19° C. All these cones are to be obtained at about one cent apiece from the Royal Prussian Porcelain Manufactory of Berlin, so well known to chemists. It was at first our intention to use the high numbers of the large-sized Seger cones as standards. On melting down several of them, measuring the temperatures at the same time with the Le Chatelier pyrometer, it was found that the fusions were completed at temperatures much lower than called for by the numbers of the cones. It did not lie within the province of the work contem-

[1] Thonindustrie-Zeitung, 1886, pp. 135, 145, 168, 229; 1888, pp. 152, 162.
[2] Ibid, 1892, p. 155.

plated to measure accurately the melting-points[1] of these cones; so it was decided to adopt the Le Chatelier pyrometer, against the results of which no objection has ever been raised. This pyrometer has been repeatedly described.[2] The small change required to adapt the instrument to the furnace consisted in fastening the clay cylinders ($\frac{3}{8}$ inch in diameter), through which the thermal wires pass, with platinum wires to an electric-light carbon instead of inserting them in the iron pipe commonly used, as this could not be safely subjected to the temperature of the furnace, and, moreover, would have absorbed too much heat. The change was not wholly satisfactory, because the carbon burns off and leaves the binding of the wire loose. A better arrangement is to choose small-sized clay cylinders ($\frac{3}{16}$ inch in diameter) for the thermal wires, and inclose them in a thin clay tube, which can stand sudden changes of temperature.

The form adopted for the test-pieces was that of the large-sized Seger cone. As the cones are not absolutely uniform in size, the dimensions $\frac{3}{4}$ by $\frac{3}{4}$ by $\frac{7}{8}$ inch for base and $2\frac{3}{8}$ inches for the sides were selected, after measuring a number of the originals, as being the best average. It will be noted that the dimensions differ somewhat from those usually quoted, and given on a preceding page.

The clay and other substances used in the experiments were all decidedly finer than what would pass through a 100-mesh sieve. They were first mixed dry, either by hand or mechanically in a Morrell agate mortar, then moistened on a glass plate with just enough water to render them plastic, and then worked with the spatula. To the water 5 per cent. of dextrine was added, when it was found necessary to give the cone additional firmness. The mould used (Figures 10 and 11) consists of three blocks of oiled wood held together by two 3-inch clamps. In making the cones two parts, A and B, of the mould are clamped together, the clay-mixture is pressed in with the spatula, the third part, C, is clamped on; the clay is pressed in firmly from the open base with a suitable piece of wood to insure a good edge and a sharp point, and the mould is then carefully taken apart. The samples were air-dried

[1] For the discussion, see *pro:* Thonindustrie-Zeitung, 1887, pp. 43, 84, 125, 197, Seger; p. 2, Heintz; pp. 52, 81, Hülsmann; p. 185, Hecht; and *con:* Thonindustrie-Zeitung, 1887, pp. 43, 87, Bischof; 1888, p. 61, Jochum.

[2] Le Chatelier, Journal de Physique, 2d series, VI, January, 1887; Génie Civil, March 5, 1887; Howe, Eng. and Min. Jour., October 11, 1890; Struthers, School of Mines Quarterly, XII, 143, and XIII, 221; Berg. und Hütten. Zeitung, 1892, 277, 301, 310; and Roberts-Austen, "Recent Advances in Pyrometry," Trans. Am. Instit. Mining Engineers, Vol. XXIII.

from fifteen to twenty hours, then slowly heated on an iron plate over a Bunsen burner and placed in the furnace near the flue, where they remained until red-hot, when they were transferred to their position

Fig. 10.

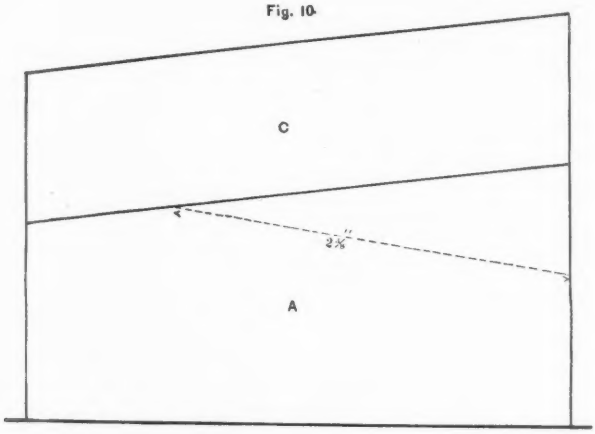
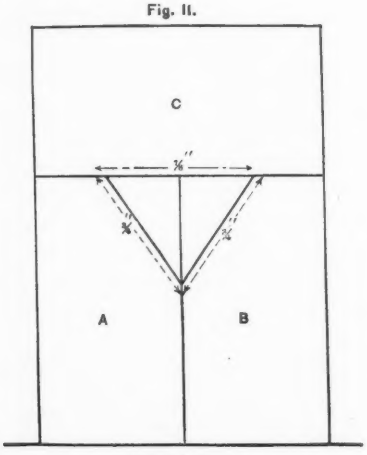


Fig. 11.



CONE-MOULD.

$4\frac{1}{2}$ inches from the nozzle, where the flame would play squarely upon them. To prevent their sticking to the bottom, it was covered with a thin layer of Mt. Savage clay. The criterion of fusion was the same

as that of the Seger cone, but when a sample bent over so that it was wholly below the flame, it was considered to have been fused, though the apex might not quite touch the base. After each experiment and the subsequent measuring of the temperature, the furnace was somewhat cooled down by shutting off the gas. The air was still allowed to pass through for a few minutes, and was then shut off, while the samples were taken out and replaced by new ones, when the air was turned on again and followed by the gas, the amounts of both being quickly increased to the desired degree. The proportions were so regulated that the flame should be slightly smoky.

4. *The Method.* — The method followed is based on the use of calcium carbonate as a flux. The amount of lime it is necessary to add to a weighed quantity of clay to form a fusible compound at a certain elevated temperature will form the criterion of the refractory value of the clay. Åkerman[1] has shown how the fusibility of silicate of lime is increased by successive additions of alumina. Cramer[2] got up, in 1887, a series of cones composed of Zettlitz kaolin and increasing proportions of marble to take the place of Bischof's standard clays. While Seger[3] highly approved of the series as far as the different degrees of fusibility were concerned, he made the objection that the mixtures melted down suddenly at the critical temperatures, while the melting down of clay is slower and more gradual. The writers' experiments show that this sudden collapse of a cone takes place only with very fusible mixtures (*e.g.*, cone No. 5), and that with refractory mixtures the bending over of a cone takes place in a way that is very similar to that of Seger's own cones. As lime is a very powerful flux, and would, therefore, have a strong effect if added, even in small proportions, to a fire-clay, it seemed advisable to try and weaken this effect by diluting with silica and using the mixture instead of the stronger pure calcium carbonate. Experiments of this character were carried on with clay from Mount Savage, Maryland, and with kaolin from Blanford, Massachusetts. A third set of experiments was made with a common brick-clay from Cambridge, Massachusetts. The method here followed was that of Bischof (see page 9) of toning up a clay with alumina, the strength of which has been weakened by silica.

[1] Stahl und Eisen, 1886, pp. 281 and 387; abstracted in Jour. I. and S. Inst., 1886, p. 310.

[2] Thonindustrie-Zeitung, 1887, p. 197; see also Bischof, Thonindustrie-Zeitung, 1888, pp. 38 and 50.

[3] Ibid, 1888, p. 153.

Table III gives the composition of the materials used in the experiments.

5. *Experiments with Fire-clay from Mount Savage, Maryland.* — The clay experimented upon belongs to the hard variety;[1] it has a conchoidal fracture; its color varies from light gray to dark chocolate brown; it disintegrates very slowly when exposed to the air and is plastic only when ground very fine. It is infusible before the blowpipe.

The results of the experiments with the light variety are brought together in Table IV and illustrated by Figure 12.

Experiments Nos. 1 to 4, in which pure calcium carbonate was added to the clay, form a good series, for the fusibility increases regularly with the additions of the flux. Cones Nos. 1 and 2 are quite fused, No. 3 is just fused, while No. 4 is only glazed and not bent over. The critical mixture contains, however, only between 5 and 10 per cent. of the flux, which is a very small quantity of reagent to produce such a decided result.

Experiments Nos. 5 to 8, where equal parts of silica and calcium carbonate are used, show little improvement over those with calcium carbonate alone. That cone No. 5 should have melted as soon as full gas had been turned on was to be expected from its low refractory quotient. It is the only example of the sudden fusion of the clay-lime mixture objected to by Seger that occurred in the experiments. The critical mixture contains from 10 to 20 per cent. of the flux. The temperatures are lower than might have been expected from the refractory quotient.

Experiments Nos. 9 to 11, with silica to calcium carbonate as 3 to 1, make a decidedly better showing than those with silica and calcium carbonate in equal parts. The critical mixture contains between 20 and 30 per cent. flux, and while the temperatures are higher than before, viz., 1510° C. *vs.* 1440° C., the difference is not great enough to invalidate the comparison.

Experiments Nos. 12 to 15 represent the mixtures of clay with the flux, five silica to one calcium carbonate, which is a further step in advance. Cone No. 12 shows good fusion; No. 13 is less completely bent; No. 14 is just a little inclined; and No. 15 is only glazed and beaded at the apex. The critical mixture contains from 30 to 40 per cent. of flux.

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[1] See R. A. Cook, Trans. Am. Instit. Mining Engineers, Vol. XIV, p. 698.

TABLE III.—ANALYSES OF MATERIALS.

Name of Material.	Al_2O_3.		SiO_2.				RO.							Loss by ignition.	O in $Al_2O_3 \div 3O$ in RO.	O in $SiO_2 \div 3O$ in RO.	O in $SiO_2 \div O$ in Al_2O_3.	Refractory Quotient.	
	Total per cent.	Oxygen, per cent.	Combined per cent.	Non-combined per cent.	Total per cent.	Oxygen, per cent.	MgO per cent.	CaO per cent.	Na_2O per cent.	K_2O per cent.	Fe_2O_3 per cent.	Total per cent.	Oxygen, per cent.					Bischof R. Q. B.	Seger R. Q. S.
Fire-clay, Mt. Savage, Maryland.[1]	29.10	13.56	28.35	31.84	60.19	32.08	trace.	....	0.	03	0.89	0.92	0.18	9.90	25.11	59.41	2.36	10.64	35.81
Kaolin, Blanford, Mass.[2]	31.76	14.80	.....	.....	52.03	27.73	0.54	trace.	trace.	trace.	trace.	0.54	0.22	15.55	22.42	42.01	1.87	11.99	34.45
Brick-clay, Cambridge, Mass.[3]	28.90	13.46	18.04	30.95	48.99	26.11	3.66	7.10	4.73[4]	Cl 0.13 SO_3 0.20	4.32	19.81	5.57	2.98	0.80	1.56	1.93	0.41	1.22
Quartz, Berkshire, Mass.	.....	.....	.....	.....	99.88	53.24	....	....	....	....	0.12[5]	0.12	0.02	....	.....	.....	.....	.....	.....
Alumina, Syracuse, N. Y.[6]	98.46	45.88	.....	.....	0.25	0.13	....	....	0.50[7]	....	0.04	0.54	0.13	0.75	.....	.....	.....	.....	.....
Calcium carbonate	.....	.....	.....	.....	.. ..	....	....	56	....	....	....	.....	.....	44	.....	.....	.....	.....	.....

[1] Kinnicut and Rogers, Journal of Analytical and Applied Chemistry, Vol. V, p. 542; Eng. and Mining Journal, December 12, 1891.
[2] Norton, Technology Quarterly, Vol. III, p. 231.
[3] Card — Thesis in Geological Department, Massachusetts Institute Technology, 1892.
[4] Equivalent to 7.17 K_2O.
[5] Assumed; previous analysis having shown the main impurity to be iron.
[6] Solvay Process Co.
[7] Equivalent to 0.75 K_2O.

TABLE IV.—EXPERIMENTS WITH FIRE-CLAY FROM MOUNT SAVAGE, MARYLAND.

Number of Experiment and Cone.	Components of Mixture.			Composition of Mixture.						Refractory Quotient.		Temperature, °C.	Remarks.
	Clay, per cent.	Quartz, per cent.	Calcium carbonate, per cent.	Al_2O_3 per cent.	O per cent.	SiO_2 per cent.	O per cent.	RO per cent.	O per cent.	Bischof R. Q. B.	Seger R. Q. B.		
.....	100	.....	.....	29.10	13.56	60.19	32.08	9.92	0.18	10.64	35.81	.....	Added for the sake of comparison.
1	80	.....	20	23.28	10.85	48.15	25.66	11.94	3.34	0.45	1.54	1470	Were together in the furnace, and were removed together. No. 1 fused before No. 2.
2	85	.....	15	24.73	11.53	51.16	27.26	9.18	2.55	0.63	2.14	1470	
3	90	.....	10	26.19	12.20	54.17	28.87	6.43	1.76	0.97	3.28	1580	Were together in the furnace, and were removed together. No. 3 fused; No. 4 only superficially glazed.
4	95	.....	5	27.65	12.88	57.18	30.47	3.67	0.97	1.87	6.30	1580	
5	40	30	30	11.64	5.42	54.04	28.80	17.20	4.88	0.07	0.43	.....	Melted at once when full gas was admitted.
6	60	20	20	17.46	8.13	56.09	29.89	11.77	3.31	0.22	1.04	1340	Melted quickly.
7	80	10	10	23.28	10.85	58.14	30.99	6.35	1.75	0.72	2.78	1440	Were together in the furnace; No. 7 fused slowly; No 8 but slightly glazed.
8	90	5	5	26.19	12.20	59.16	31.53	3.63	0.96	1.63	5.10	1440	

TABLE IV. — EXPERIMENTS WITH FIRE-CLAY, FROM MOUNT SAVAGE, MARYLAND. — *Concluded.*

Number of Experiment and Cone.	Components of Mixture.			Composition of Mixture.						Refractory Quotient.		Temperature, °C.	Remarks.
	Clay, per cent.	Quartz, per cent.	Calcium, carbonate per cent.	Al_2O_3 per cent.	O per cent.	SiO_2 per cent.	O per cent.	RO per cent.	O per cent.	Bischof R. Q. B.	Seger R. Q. B.		
9	60	30	10	17.46	8.13	66.07	35.22	6 19	1.71	0.36	1.95	1420	Fused slowly.
10	70	22.5	7.5	20.37	9.49	64.61	34.43	4.87	1 33	0.65	3.02	1510	Were together in the furnace. No. 10 fused slowly; No. 11 is glazed and has a rounded point.
11	80	15	5	23 80	10.85	63.13	33.65	2.85	0 81	1.44	5.90	1510	
12	40	50	10	11.64	5.42	74.02	39.45	6.03	1.68	0.14	1 22	1470	Together in furnace; temperatures are averages of two series of experiments; both fused slowly; No. 12 is seen to be more fused than No. 13.
13	50	41.7	8.3	14.55	6.78	71.74	38 24	4.74	1.34	0.29	1.98	1470	
14	60	33.3	6.7	17.46	8.13	69.37	36.97	4.34	1.18	0.50	2 80	1600	Together in furnace; No. 14 somewhat fused; No. 15 glazed and beaded at apex.
15	70	25	5	20.37	9.49	67.10	35.76	3.47	0.93	0.90	4.30	1600	

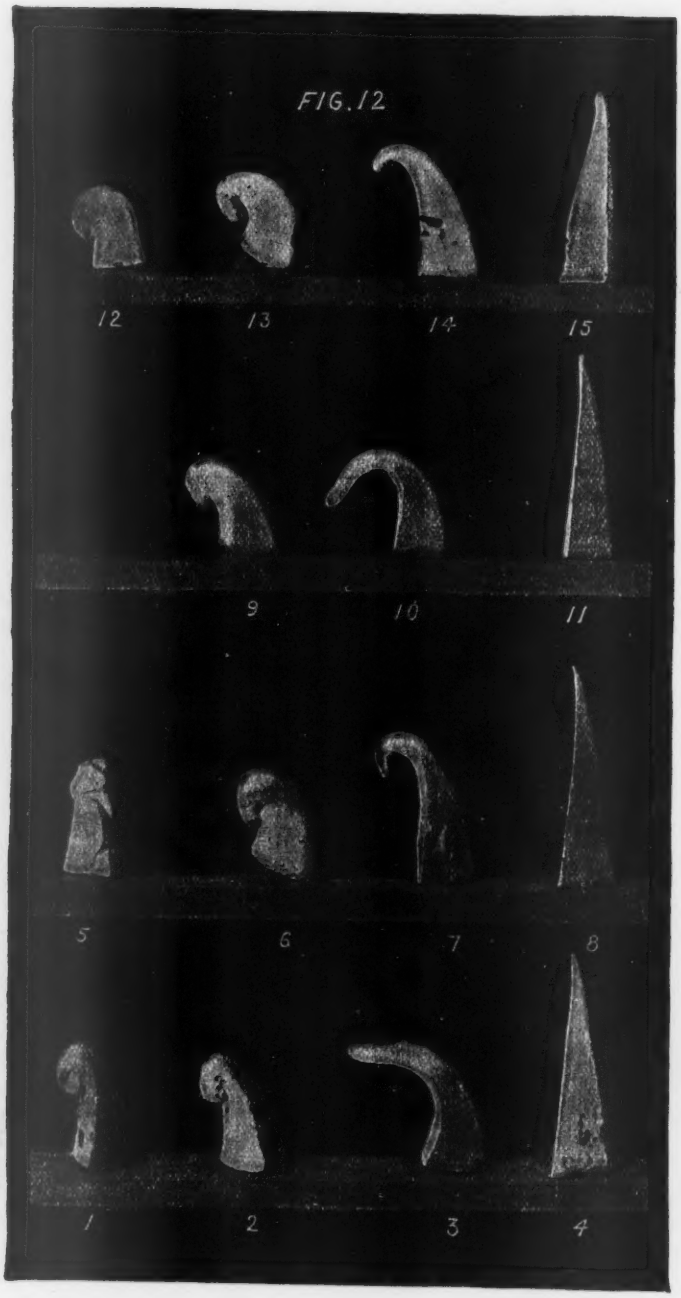
FIG. 12
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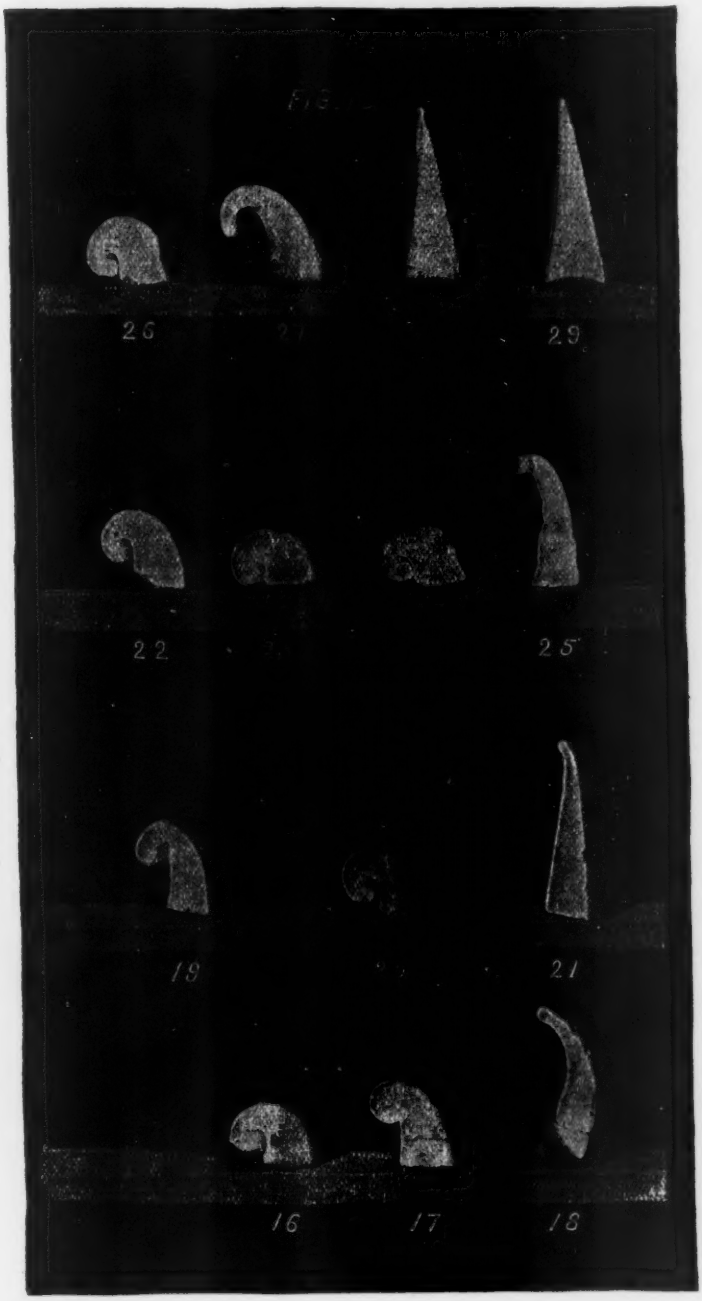
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The proportion of five silica to one calcium carbonate is the highest that was used. A mixture still richer in silica than this might possibly be better for fire-clays less refractory than that from Mount Savage; but five silica to one calcium carbonate is sufficient so long as the mixture fulfills the necessary condition of being weak enough to be used in considerable quantities without having too great an effect. This is important, as there must be difference enough in the amounts added to the various clays to afford a satisfactory scale for measuring their fusibility.

6. *Experiments with kaolin from Blanford, Massachusetts.* — The kaolin from Blanford, Massachusetts,[1] used in these experiments is soft, pinkish white, and slightly plastic. It has a high degree of purity, as seen by the analysis (Table III), and is infusible before the blowpipe. The sample received, weighing about twelve pounds, was a mixture of friable kaolin and more or less disintegrated crystals of mica and quartz. As it was desired to have the purest kaolin obtainable, the original sample was dried and worked without grinding through a series of screens to remove the mica and quartz, that only which had passed through a 100-mesh sieve (25 per cent. of the original amount) being reserved for the experiment after it had received a final grinding in a Morrell agate mortar.

The experiments Nos. 16 to 29 were carried on in the same manner as those with the clay from Mount Savage. The results obtained are brought together in Table V, and the cones are represented by Figure 13. If they are compared with those obtained with Mount Savage clay it will be seen, first, that the critical mixtures in the corresponding cases contained the same amount of flux, and secondly, that those having a higher refractory quotient require also a higher temperature. An exception to this is found with the flux containing five silica and one calcium carbonate where cones Nos. 26 to 29, with a large refractory quotient, show lower temperatures than cones Nos. 12 to 15 with a small one. The explanation is wanting.

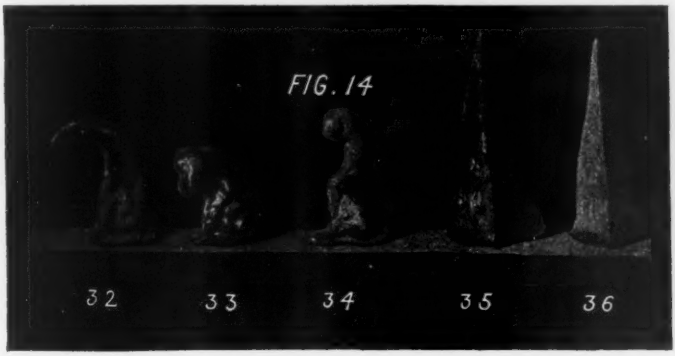
7. *Experiments with Brick-Clay from Cambridge, Massachusetts.* — This clay is largely used in the brickyards of Cambridge. It is soft, light gray, and plastic, shows a considerable number of impurities, and is readily fusible. It was chosen to test in the new furnace Bischof's method of toning up a low grade clay with a mixture of equal parts

[1] Crosby, Technology Quarterly, Vol. iii, p. 228.

of silica and alumina, so it shall fuse only at an elevated temperature. The experiments are recorded in Table VI, and of the cones obtained, Nos. 30 to 36, only Nos. 32 to 36 are shown in Figure 14.

Experiments Nos. 30 and 31 show how readily fusible the clay is; in fact, the specimens, upon heating, quickly swelled up into a spongy mass; even with 20 per cent. of stiffening ingredient, fusion occurred at 1,300° C., and it required from 40 to 50 per cent. of the ingredient to enable the clay to resist a high temperature.

8. *Conclusion.* — In the foregoing experiments a definite standard temperature has not been sought. It seemed of greater importance to study first the behavior of several series of mixtures of clay, silica, and lime at elevated temperatures, and to measure these. Of the



fluxes tested, the mixtures of three silica to one calcium carbonate and five silica to one calcium carbonate have proved valuable; and further series of tests with a number of analyzed refractory clays will be needed to decide whether the proportion of five silica to one calcium carbonate, which has so far proved the better of the two, can maintain its position or will have to yield to a mixture that is more siliceous. In these final experiments it will be necessary to maintain a definite temperature (which is easily done with the furnace) and make it the standard. Experience so far seems to show that 1,500° C. is the best. It is also proposed to make a parallel series of tests by Seger's direct method, and compare the results with those from the indirect silica-lime method.

TABLE V. — EXPERIMENTS WITH KAOLIN FROM BLANFORD, MASSACHUSETTS.

Number of Experiment and Cone.	Components of Mixture.			Composition of Mixture.						Refractory Quotient.		Temperature, °C.	Remarks.
	Kaolin, per cent.	Quartz, per cent.	Calcium carbonate, per cent.	Al_2O_3 per cent.	O per cent.	SiO_2 per cent.	O per cent.	RO per cent.	O per cent.	Bischof R. Q. B.	Seger R. Q. S.		
.....	100	.....	.....	31.76	14.80	52.03	27.73	0.54	0.22	11.99	34.45	.....	Added for sake of comparison.
16	85	.....	15	26.99	12.58	44.22	23.57	8.86	2.58	0.86	2.49	1490	Were together in furnace. No. 16 well fused; No. 17 less so.
17	90	.....	10	28.58	13.32	46.83	24.96	6.09	1.79	1.32	3.80	1490	
18	95	.....	5	30.17	14.06	49.43	26.34	3.31	1.00	2.50	7.18	1640	Only well bent.
19	70	15	15	22.23	10.36	51.40	27.39	8.79	2.56	0.51	1.85	1370	Fused.
20	80	10	10	25.41	11.84	51.61	27.51	6.04	1.77	0.96	3.18	1490	Fused.
21	90	5	5	28.58	13.32	51.82	27.62	3.29	1.00	2.14	6.58	1610	Only beaded at the apex.
22	50	37.5	12.5	15.88	7.40	63.47	33.83	7.31	2.12	0.25	1.45	1330	Fused.

TABLE V.—EXPERIMENTS WITH KAOLIN FROM BLANFORD, MASSACHUSETTS.—*Concluded.*

Number of Experiment and Cone.	Components of Mixture.			Composition of Mixture.						Refractory Quotient.		Temperature, °C.	Remarks.
	Kaolin, per cent.	Quartz, per cent.	Calcium carbonate, per cent.	Al_2O_3 per cent.	O per cent.	SiO_2 per cent.	O per cent.	RO per cent.	O per cent.	Bischof R. Q. B.	Seger, R. Q. S.		
23	60	30	10	19.06	8 88	61.18	32.61	5.96	1.74	0.46	2 16	1500	Fused.
24	70	22.5	7.5	22.23	10.36	58.89	31.39	4.60	1.36	0.83	3.37	1560	Fused.
25	80	15	5	25.41	11.84	56 60	30.17	3.25	0.98	1.58	5.61	1660	Only well bent.
26	60	33.33	6.67	19.06	8.88	64.51	34.38	4.09	1.20	0.63	3.10	1340	Fused.
27	70	25	5	22.23	10.36	61.39	32.72	3.21	0.96	1.13	4.73	1380	Fused half down.
28	80	16.67	3.33	25.41	11.84	58.53	31.06	2.32	0.71	2.11	7.67	1580	Only slightly beaded at the apex.
29	90	8.33	1.67	28.58	13.32	55.14	29.39	1.43	0.46	4.37	14.02	1580	Unaffected.

TABLE VI.—EXPERIMENTS WITH BRICK-CLAY, FROM CAMBRIDGE, MASSACHUSETTS.

Number of Experiment and Cone.	Components of Mixture.			Composition of Mixture.						Refractory Quotient.		Temperature, °C.	Remarks.
	Brick-clay, percent.	Quartz, per cent.	Alumina, per cent.	Al_2O_3 per cent.	O per cent.	SiO_2 per cent.	O per cent.	RO per cent.	O per cent.	Bischof R. Q. B.	Seger R. Q. S.		
.....	100	.....	.....	28.90	13.46	48.99	26.11	19.81	5.57	0.41	1.22	.....	Added for the sake of comparison.
30	90	5	5	30.93	14.41	49.09	26.16	17.86	5.02	0.52	1.48	?	Fused at once when half the gas was turned on.
31	85	7.5	7.5	31.94	14.88	49.15	26.19	16.88	4.74	0.59	1.64	?	
32	80	10	10	32.96	15.35	49.20	26 22	15.91	4.47	0.67	1.81	1300	Fused.
33	70	15	15	34.99	16.30	49.31	26.28	13.96	3.92	0.86	2.24	1450	Fused.
34	60	20	20	37.03	17.25	49.42	26 34	12.02	3.37	1.11	2.82	1610	Fused.
35	50	25	25	39.06	18 17	49.53	26.39	10.23	2.85	1.46	3.58	1610	Glazed on outside but not fused.
36	40	30	30	41.09	19.15	49.66	26.47	8.12	2.27	2.14	4.95	?	Unaffected.

ON AN APPARATUS FOR THE MEASUREMENT OF COEFFICIENTS OF SELF-INDUCTION AND THE INVESTIGATION OF THE PHENOMENA OF ALTERNATING CURRENTS.[1]

By FRANK A. LAWS, S.B.

Received January 11, 1894.

THE increasing use of alternating currents in telephony and electric lighting has, during the last few years, directed attention to the measurement of coefficients of self-induction. In this paper certain apparatus devised for this purpose, together with methods for its use, will be described. Further discussion of the various methods of measurement proposed and of experimental results obtained is reserved for a later article.

For investigations pertaining to telephony it is particularly desirable to measure inductances by means of alternating currents of suitable known frequencies and of the same order of magnitude as those used in practice. In all such work the reduction of the results is greatly simplified if the E. M. F. employed follows the sinusoidal law.

Therefore the aim at the outset was to produce a dynamo whose E. M. F. should vary in this manner, and whose frequency of alternation should be about that which is normal in telephonic work. Under these requirements there have been designed in the Rogers Laboratory two dynamos or arrangements of dynamos. The first of these was planned during the winter 1890–91, and was used by Mr. L. Derr in connection with his thesis in 1891–92. This machine was provided with a stationary armature having Lord Kelvin's zigzag winding on the outer surface of a hollow cylinder. This was placed in the gap between a star-shaped piece of iron and a disk with a corresponding star-shaped opening, the two pieces being similarly and concentrically

[1] Read at a meeting of the American Academy of Arts and Sciences, January 10, 1894.

placed and forming the pole pieces of the machine. Owing to the shape of the pole pieces the field between them is variable, being denser at the points of the stars, so that when the field moves past the armature an E. M. F. will be set up in the latter.

One disadvantage of this design is that the E. M. F. is small, owing to the very large non-effective field; for it is only the variation of the field that is of service in producing the electro-motive force. By properly shaping the pole pieces a curve of electro-motive force was obtained, which, when plotted, was found to be nearly sinusoidal in form.

The second machine was constructed by Messrs. C. L. Norton and P. H. Thomas, of the class of 1893, and forms the subject of the present paper. The special form of dynamo used was designed in accordance with a suggestion from them. The frequency is somewhat low, being 400 complete alternations per second. When another machine is built it will be so designed that the superior limit will be raised to 2,000 complete periods per second.

Both the machine of 1890 and that of 1892 embody the same general features. Each has two independent armatures, one fixed, the other movable in phase relation to the first. This relation is capable of measurement. At the outset it was determined that in these machines the armatures should contain no iron and that they should remain stationary, in order to eliminate any possible microphonic action at the brushes.

The machine, which is shown in place ready for use in Figure 1, will now be described. It consists, in brief, of two dynamos, with revolving fields mounted on one shaft to insure definite phase relation. The armature of one is fixed, while that of the other may be given any desired angular advance or retardation in reference to the first by means of a tangent screw. This advance can be read off from the graduated head of the screw. The fields are independent of one another. In addition to the dynamos the shaft carries a contact arrangement for mapping wave-forms, and a stroboscopic disk for determining the speed of rotation.

One of the field magnets is shown in plan in Figure 3 and in section in Figure 2. It consists of two star-shaped pieces of cast iron, keyed to the shaft and having hubs of such a length that the faces of the teeth are $\frac{5}{16}''$ apart, thus leaving a gap in which is the armature, $\frac{1}{4}''$ thick. The castings are recessed to receive the field coils,

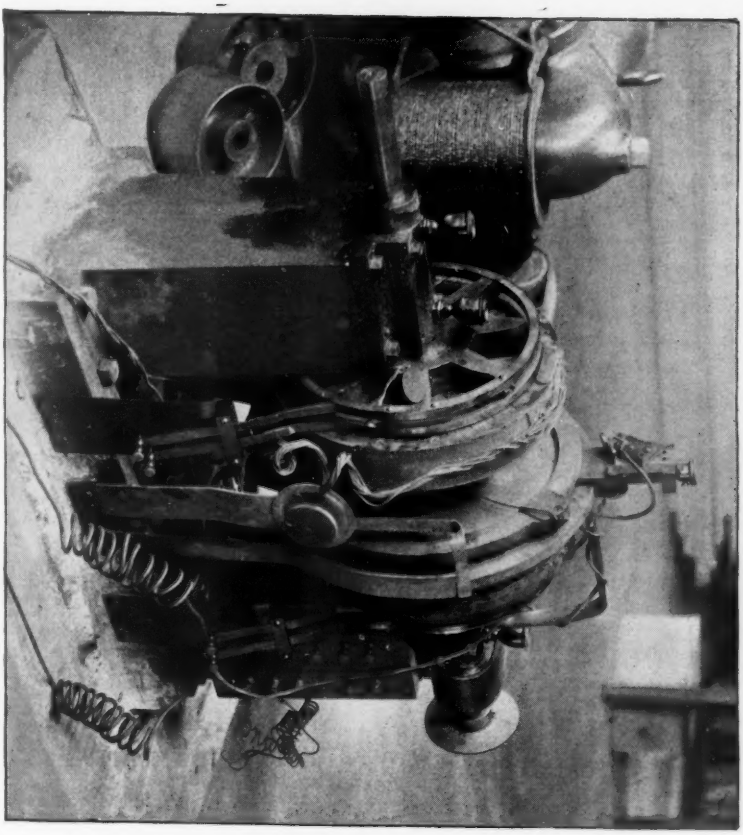


FIGURE 1.

which are about one square inch in section and contain 250 turns of No. 16 B. & S. double cotton-covered wire. The coils were wound on forms, paraffined and taped, and were inserted when the machine was

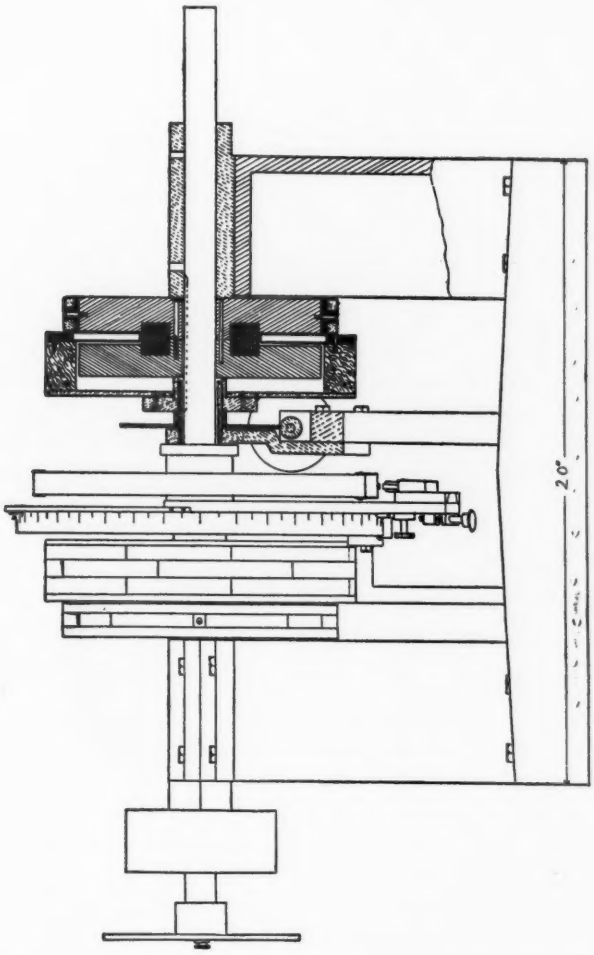


FIG 2 ELEVATION AND HALF SECTION THROUGH DYNAMO A

assembled. The terminals are brought out through bushed holes and fastened to composition collector rings which are carried and insulated by blocks of vulcanite mounted on the tips of the teeth of one of the

castings. The brushes of spring copper are supported from the base plate. The eight teeth were milled from the round by a special Brown & Sharpe cutter, and have the form of a sinusoid laid off radially from the base circle. Of course, owing to the spreading of the lines of force, the particular form to be given to the teeth in order to obtain the best action can only be obtained by trial.

The armature consists of a vulcanite disk, $10\frac{1}{4}''$ diameter, $\frac{1}{4}''$ thick, having a $4''$ hole in the middle. From this hole radiate 16 equally spaced saw-cuts $\frac{3}{16}''$ deep, $\frac{1}{16}''$ wide, and $2\frac{1}{4}''$ long, the outer extremities of alternate pairs of cuts being connected by grooves concentric with the disk. In these cuts and grooves the armature wires are laid in shellac. The windings at present consist of three sections having respectively 10, 10, 20 turns of No. 30 B. & S. copper wire. The total resistance is about 10 ohms. The manner of winding as well as the action of the dynamo, by varying the length of active wire, are evident from Figure 3. The armatures are carried by built-up hard-wood rings $10\frac{1}{4}''$ outside diameter, $8\frac{1}{4}''$ inside, and $1\frac{9}{16}''$ deep. The ring in one dynamo is attached to a brass disk and hub which fit the shaft and are rigidly bolted to the frame of the machine.

In the other dynamo, the armature, ring, disk, and hub are attached to a worm-wheel, and the whole is movable on a sleeve supported firmly from the frame of the machine. Through this sleeve passes the shaft without contact. The worm-wheel gears into a tangent screw provided with a divided head, the gearing being such that 1° on the wave form is represented by 20° on the head. Backlash is prevented by a spiral spring. See Figures 2 and 3.

Between the two dynamos is a brass disk, keyed to the shaft and provided with an insulated collector ring and contact point. By the side of this disk is a radial arm, revolving freely about the shaft and capable of being clamped at any desired point to a fixed graduated circle. The arm carries the contact spring, made of watch spring and supported on its lower side very near its extremity to prevent the lengthening of the arc of contact by vibration. The spring can be moved out of contact with the point by a fine-pitched screw. This contact arrangement we have found to work satisfactorily at as many as 3,000 revolutions per minute.

The shaft of the machine is of steel $1''$ diameter, $29''$ long, and runs in composition bearings, each of which is $5\frac{1}{2}''$ long. The frame of the machine is heavy, weighing 175 pounds, and is designed so

as to be very rigid. Driving is effected by means of a 2″ belt running over a 5″ pulley. The motor (1 H. P.) is of the Sprague type. Variations of speed are obtained by the use of pulleys of different sizes on the motor shaft.

Both machine and motor rest on a brick pier, the machine being set in sulphur; mechanically the arrangement leaves nothing to be

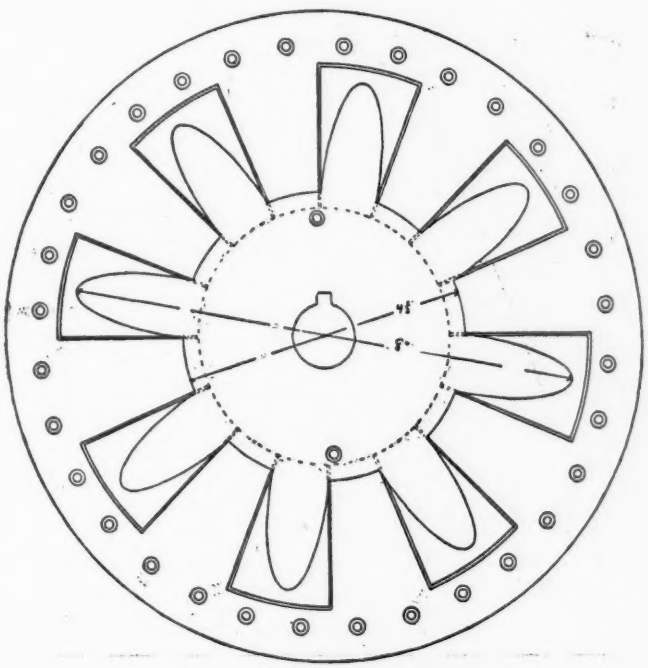


FIG. 3 FIELD MAGNET AND ARMATURE

desired. It has been run continuously at the rate of 3,000 revolutions per minute, without perceptible jarring.

The machine was at first supplied with a mechanical counter which could be thrown on or off by means of an electro-magnet operated by a key. We found, however, that the arrangement was unsatisfactory, as variations of speed were introduced by its friction and inertia. Moreover, such an arrangement gives only the average speed during a given time; we therefore abandoned this counter and adopted a

stroboscopic device. A ray of light is reflected upon the revolving segmented disk from a mirror attached to an electrically driven tuning-fork of known rate. With such an arrangement the desired speed may be attained and variations from it measured by noting the apparent motion of the disk.

The first test to which the apparatus was put was to obtain the

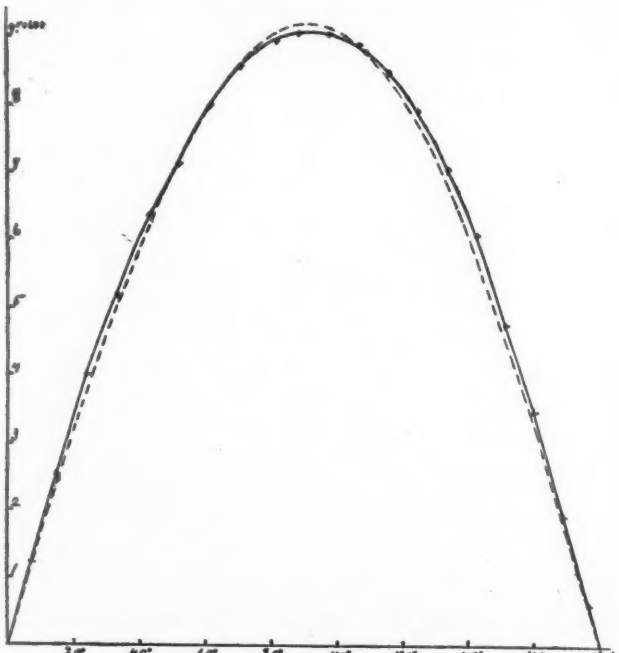


FIG 4 ARMATURE A. TRUE SINE CURVE DOTTED

judgment of a person having a trained ear as to the quality of the tone produced by its current in a telephone. His opinion was that the tone was pure, only the fundamental being detected. The wave form was then mapped.

In planning this work it occurred to us to employ the method of projection of potentials whenever it was necessary to measure a P. D. or E. M. F. at any instant. The opposing P. D. was obtained by the fall of potential due to the passage of a direct current through a suit-

able resistance. As the opposing P. D. was not alternating, the above mentioned contact arrangement was used in place of the ordinary key, and its value was determined by a suitable Weston voltmeter. This method of dealing with instantaneous E. M. F.'s was originally suggested by Professors Foster and Maxwell, their object being to obtain a balance between a known E. M. F. and the P. D.

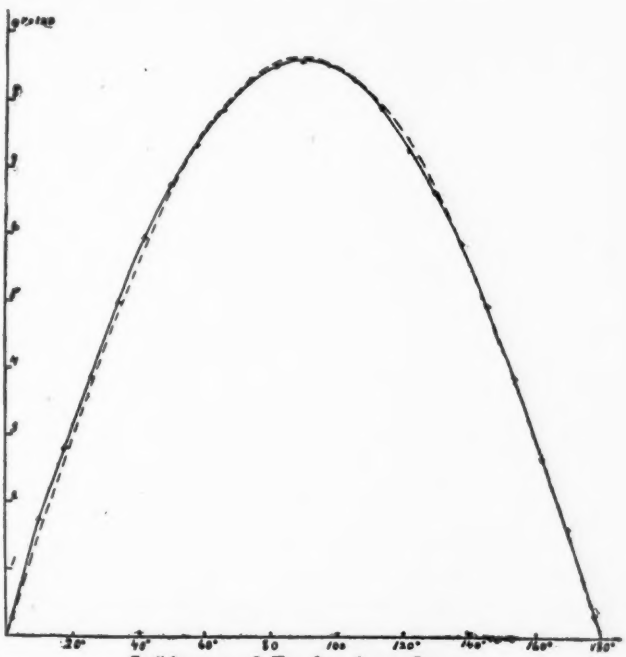


FIG 5 ARMATURE B. TRUE SINE CURVE DOTTED.

between the terminals of a resistance through which a current of known absolute magnitude was flowing.[1]

In order to obtain sensitiveness at the final balancing a condenser one microfarad in capacity was inserted in shunt with the galvanometer, the discharge of the condenser serving to increase the deflection. The galvanometer was of 3,000 ohms resistance. A telephone was used to obtain the preliminary balance. In Table I are given the

[1] Telegraphic Journal, 2, 1874, 317.

TABLE I. DETERMINATION OF WAVE FORM.

Armature A.			Armature B.	
Ampere turns, 2,875.			Ampere turns, 2,150.	
Speed, 1,465.				
Revs. of Mic. Head.	E. M. F. in volts.	Check.	Position of Contact.	E. M. F. in volts.
0	+ .49	+ .48	11°	+ 1.00
½	— .91	— 1.20	10	— .26
1	— 2.52	— 2.53	9	— 1.72
1½	— 4.01	— 4.01	8	— 2.80
2	— 5.21	— 5.19	7	— 3.86
2½	— 6.38	— 6.36	6	— 4.98
3	— 7.09	— 7.21	5	— 5.93
3½	— 8.04	— 8.03	4	— 6.75
4	— 8.61	— 8.61	3	— 7.34
4½	— 9.01	— 8.96	2	— 7.86
5	— 9.11	— 9.12	1	— 8.30
5½	— 9.12	— 9.12	360	— 8.50
6	— 8.95	— 8.94	359	— 8.56
6½	— 8.52	— 8.54	358	— 8.54
7	— 8.00	— 7.95	357	— 8.30
7½	— 7.09	— 7.08	356	— 7.91
8	— 6.11	— 6.12	355	— 7.26
8½	— 4.80	— 4.80	354	— 6.62
9	— 3.53	— 3.48	353	— 5.86
9½	— 1.94	— 1.96	352	— 4.93
10	— .60	— .60	351	— 3.85
10½	+ 1.12	....	350	— 2.67
....	....	....	349	— 1.60
....	....	....	348	— .32
....	....	....	347	+ .74

results of the determination of the wave forms of both dynamos, one section of 10 wires being used. In the case of armature A (movable) a series of checks is appended. The whole series was gone through with and then repeated in the reverse direction, the person making the readings not knowing the previous results. The most probable sources of deviation are backlash, variations of field current, and change of speed. The checks show sufficient precision of the apparatus for the method of procedure to be described presently.

These results are plotted together with true sine curves in Figures 4 and 5. The curves proved to be very nearly symmetrical, so that only one half has been given. The saturation curve connecting maximum E. M. F. and field current was taken with armature A. The results are given in Table II, and are plotted in Figure 6.

TABLE II. DATA OF SATURATION CURVE.

Speed, 1,465.	
Field Current in amperes.	E. M. F. in volts.
3.40	5.56
4.12	6.16
4.93	6.74
6.10	7.40
7.08	7.70
8.06	8.10
9.38	8.52
11.12	9.23
14.40	10.10
15.00	10.18

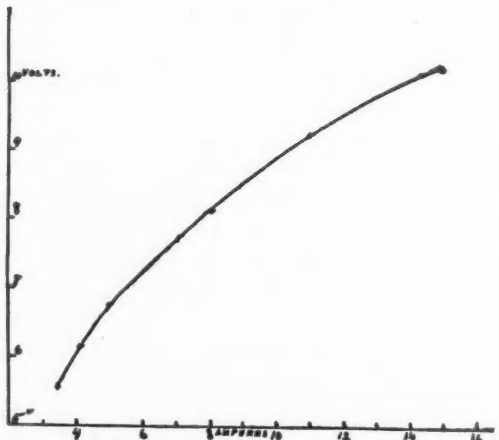


FIG. 6 SATURATION CURVE

METHODS OF USING THE MACHINE.

The following methods are all based on the assumption that we have a sinusoidal E. M. F. of known period, acting in a circuit containing only true resistances and inductances. The current at any instant will be expressed by the equation

$$i = \frac{E}{\sqrt{R^2 + P^2L^2}} \sin\left(Pt - \tan^{-1}\frac{LP}{R}\right)$$

The maximum value of the sine term being unity, we have

$$\frac{I}{E} = \frac{1}{\sqrt{R^2 + P^2L^2}}$$

I and E being the maximum current in, and maximum E. M. F. impressed upon the part of the circuit under discussion. Also the lag between current and E. M. F. is expressed by $\tan\theta = \frac{LP}{R}$. From these two equations we have

$$L = \frac{E}{IP}\sin\theta \qquad R = \frac{E}{I}\cos\theta$$

Our aim is, therefore, to obtain the values of the impedance, angle of lag, and frequency, and to calculate the coefficient of self-induction and the resistance for any given periodicity by the above formulæ.

(*a*) If we make up a circuit of the movable armature, a known resistance of negligible inductance, and the unknown coil, all in series, we may, by means of the measuring arrangement already mentioned, obtain E and I, the latter by the maximum P. D. around the known resistance. The angle θ would best be found by taking measurements on both sides of the zeros of current and E. M. F., and interpolating for the zero points. The difference of readings of the micrometer so obtained divided by 20 gives the angle θ. L and R are to be calculated by the above formulæ.

(*b*) If we have a carefully made plot like Figure 6 connecting the maximum E. M. F. and field current of one dynamo, we may proceed as follows: As the wave forms are alike, both following the sinusoidal law, we may apply Poggendorf's method of balancing E. M. F.'s directly, using a suitable telephone instead of a galvanometer. To do this make up a circuit of the stationary armature, known inductionless resistance, and unknown coil. Keep the field current of this dynamo constant. Attach the second armature through the telephone, first to the terminals of the known resistance. Adjust the phase relation for a minimum of sound in the telephone; then adjust for silence by varying the field current. Read the micrometer head and value of exciting current. Repeat this process at the terminals of the unknown coil. These measurements furnish the data necessary for the calculation of L and R. θ is given by difference of micrometer readings divided by 20, as before. Owing to lack of exact similarity of E. M. F. waves it would be necessary in practice to adjust by a minimum, annulling the fundamental.

(*c*) The trouble of taking the preliminary curve, as well as any uncertainty which its use may introduce, can be avoided by the connections shown in Figure 7.

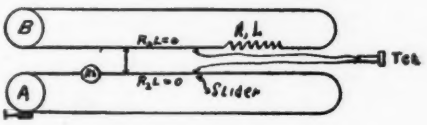


FIG. 7.

This method differs from the preceding only in the use of a derived E. M. F. for balancing and in the method of its adjustment. For convenience, give R_1 such a value that the P. D.'s around R_1 and R shall be about equal. Adjust the phase of armature A by the tangent screw, and adjust for amplitude by varying the field current, final adjustment being obtained by the slider.

Now change the connection to the terminals of the unknown coil, and again adjust for silence, making the adjustment for amplitude in this case by the slider alone. If the two values of the slider resistance are R_2 and R_3, then $\frac{I}{E} = \frac{R_2}{R_1 R_3}$. θ is given by the micrometer head as before.

(*d*) We may use a differential telephone, that is, a telephone having two opposed windings of equal influence and resistance, in the manner shown in Figure 8.

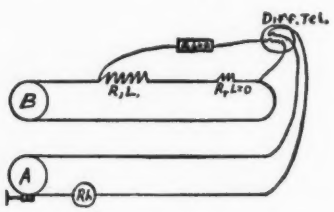


FIG. 8.

R_T is a resistance equal to that of one coil of the telephone and of negligible inductance. Adjustment is to be made until with the same value of i_A the telephone is silent when in place, as shown, and when interchanged with R_T then $R_1 = \frac{E}{I}$. θ is given by micrometer readings as before.

(*e*) We may also use the differential telephone to indicate when an unknown inductance is neutralized by a condenser of known variable capacity, by placing one of its coils in series with the inductance and condenser and the other in series with a variable inductionless resistance R_1, shunted around the above condenser, inductance and telephone coil, if the resistance R_1 and capacity C be varied until silence is obtained. Then $L = \frac{1}{CP^2}$ and $R = R_1$. It will be desirable

to employ an air-condenser to eliminate absorption effects, though this procedure has the disadvantage of requiring a very bulky and costly condenser when small inductances are to be measured.

With this apparatus we may also determine the electrostatic capacity of a condenser when not complicated by absorption effects. For instance, by the first method, we should insert in series with the condenser an inductionless resistance of such a magnitude that the angle of advance could be determined with accuracy.

Then

$$\frac{I}{E} = \frac{1}{\sqrt{R^2 + \frac{1}{C^2P^2}}} \qquad \tan\psi = \frac{1}{CRP}$$

$$C = \frac{I}{EP\sin\psi} \qquad R = \frac{E}{I}\cos\psi$$

If $R = 0$, $\psi = 90°$ and $C = \frac{I}{EP}$.

The above are the chief uses to which the apparatus may be put. We hope in the near future to investigate the transmission of telephonic and telegraphic signals, and to study various small induction coils such as are used in telephony, as well as the errors introduced into results by the above methods owing to lack of fulfillment of the assumed law by the E. M. F.

ROGERS LABORATORY OF PHYSICS,
September, 1893.

A NEW TORSION MACHINE.

By EDWARD F. MILLER, S.B.

Received January 8, 1894.

A NEW torsion machine capable of weighing the twisting moment necessary to twist off iron bars up to 3″ diameter, and of lengths varying from 1 to 8 feet, has recently been added to the Engineering Laboratories of the Institute.

The aim of this design was to make a machine which would be accurate, easy to operate, and which would allow of a change in length of the test piece. Figures 1 and 2, taken from a photograph, give a good idea of the machine. One end is bolted firmly to two 11″ x 18″ yellow pine floor beams 12″ on centers, and serves merely to apply the twist. This twist is carried through the specimen to a weighing head hung in a movable carriage made of heavy, hard pine timber. This carriage runs on tracks, and can be moved to accommodate different lengths of specimen.

THE TWISTING END.

Power is applied to the twisting end of the machine through a 4″ belt driving a 24″ pulley on the shaft A, Figure 1. This shaft has on the inner end a hand wheel for accurately adjusting the twisting moment when using micrometers. On the same shaft is a $6\frac{3}{4}$″ diameter pinion, gearing with a 48″ gear, 4″ face on the shaft B. This 48″ gear turns freely on B, and has bolted to it a $6\frac{1}{4}$″ pinion, which in turn gears with another 48″ gear on the shaft C. The shaft C carries a strong, shrouded pinion $10\frac{3}{4}$″ diameter, gearing with a 43″ gear, 6″ face, $2\frac{1}{4}$″ pitch keyed to B. These two gears are liable to have a pressure of 12,000 pounds come on one tooth. The main shaft, which is of steel, is $4\frac{1}{2}$″ diameter for about half its length, and is then turned down with

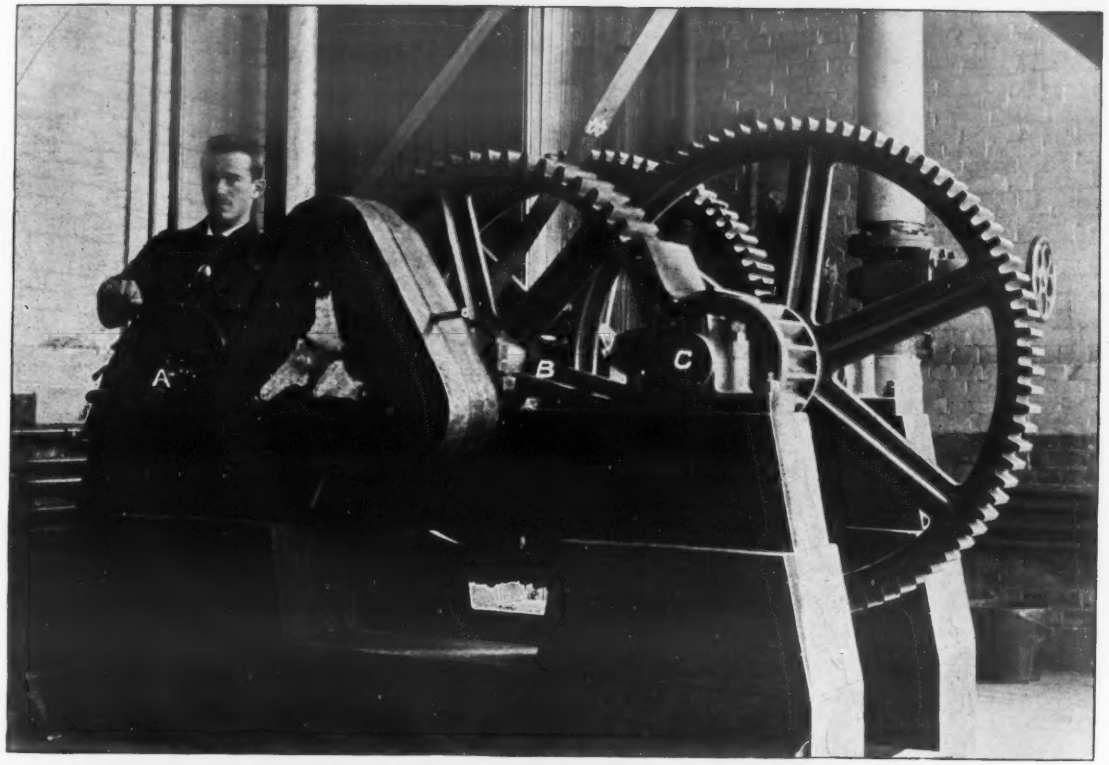


FIGURE 1.

FIGURE 2.

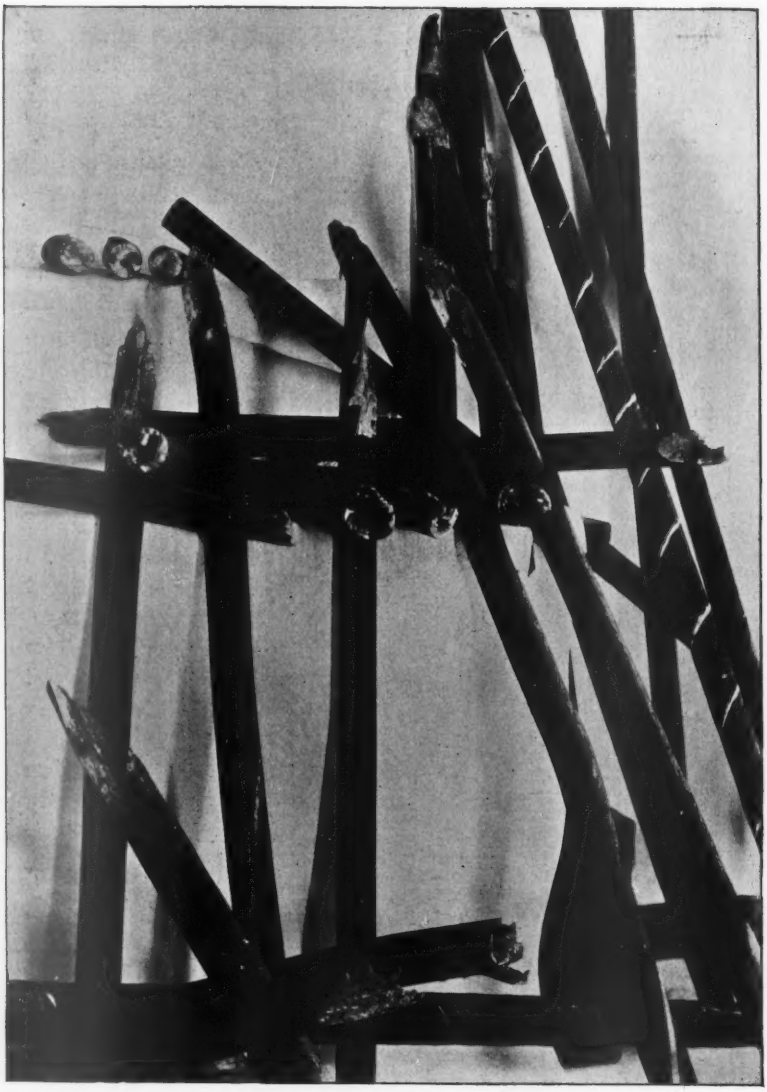


FIGURE 3.

a round corner to $3\frac{1}{2}''$ diameter under the loose gear and pinion and through the outer bearing. One of the gripping holders is keyed to the inner end of the main shaft. This shaft, with holder and gears, weighs about 2,800 pounds. The end thrust of the last train of gears is taken from the frame by two ties of $3'' \times \frac{1}{2}''$ iron joining the boxes of the shafts B and C.

The frame supporting the shafts is made of $12'' \times 12''$ and $8'' \times 12''$ hard pine timber keyed and bolted together, the bottom of the frame being spread to about six feet. There is a certain amount of force tending to turn this frame as a whole about one end, but the weight of the shafts and gears is enough to overbalance this. There are two sets of pulleys on the overhead countershaft, one set giving twice the speed of the other.

The total multiplication both in the countershaft belting and in the gears is for the slower speed.

$$\frac{24}{3} \times \frac{24}{10} \times \frac{48}{6.75} \times \frac{48}{6.25} \times \frac{43}{10.75} = \frac{4194}{1} \text{ or about 4194 to 1.}$$

The speed of the engine shafting is about 290 revolutions per minute, so that the twisting holder turns once in about $14\frac{1}{2}$ minutes.

THE WEIGHING END.

The carriage at the weighing end rests on four flanged truck wheels running on I beam tracks firmly bolted to the floor. To prevent the whole carriage from overturning, there are two hold-down wheels on one side, which bear against the under side of the upper web of the I beam. These wheels have but a small load at the full capacity of the machine. The bottom of the carriage is spread to about four feet, in order to prevent cramping on the tracks. The tracks are carried beyond the inner frame of the twisting end, so that the carriage may be brought up to the holder.

The weighing head (Figure 2) is supported by an equal armed lever hung from the top of the carriage. This head consists of two pieces of steel, $\frac{1}{2}''$ thick and $80''$ long, shaped as shown in the figure, with a gripping holder at the center and castings at either end riveted in between them. In each of the end castings there is a knife edge, the point of the knife edge pointing in the direction that that end tends to turn. These knife edges are connected to two levers (EE), one at the

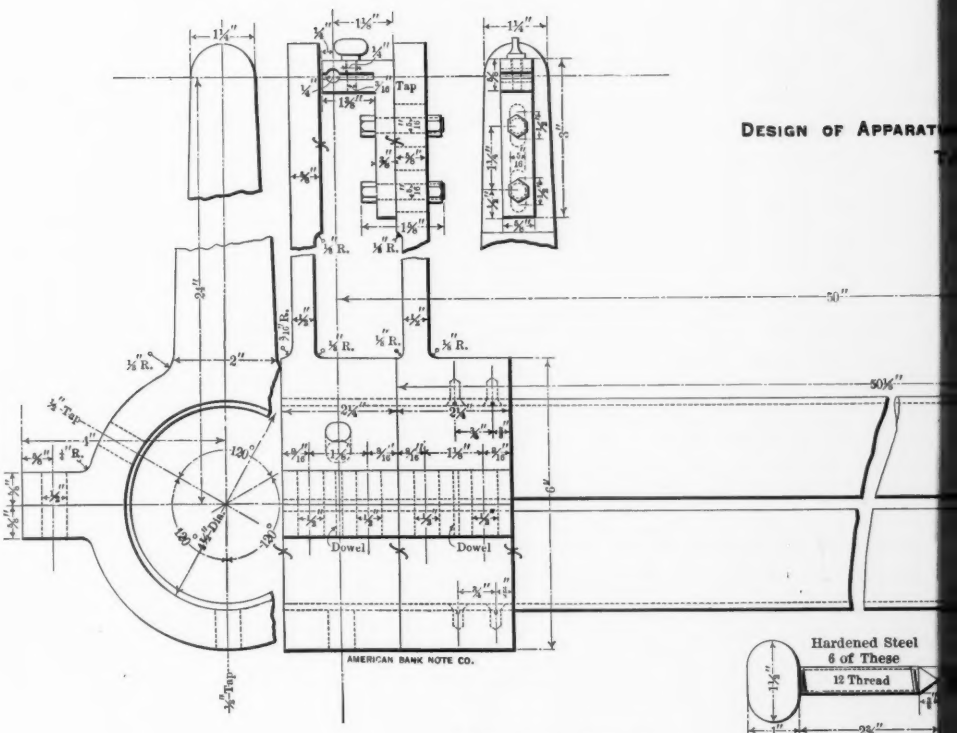
top and one at the bottom of the carriage, in such a way that the inner ends of these levers separate when a twist is applied. These levers are not exactly in the plane of the weighing head, the fixed fulcrum being moved so that the free ends of the levers swing clear of the weighing head. One spring balance takes the pull of both levers. By this means the forces at the two end knife edges are equal, opposite, and parallel, thus forming a couple. The twisting moment is then the force at a knife edge times 72, the distance between the knife edges in inches; and as the levers give a multiplication of 5 to 1, the pull at the spring balance times 360 (5 x 72) gives in inch-pounds the twisting moment on the specimen. It might be said that as the spring balance pulls out the levers will be thrown out of level; but a load of 300 pounds causes a motion of only $1\frac{1}{4}''$ at the spring balance, and the end of the lever of the weighing head is thrown out but $\frac{12}{100}''$. All the knife edges in the weighing head, as well as those in the levers, are placed in line, so that the error introduced is inappreciable.

The manner of suspending the weighing head allows of a bending or of a change in length of the specimen under test without throwing any new strains into it. The spring balance measuring the pull on the levers is shortly to be replaced by a lever and sliding weight graduated to read twisting moments directly.

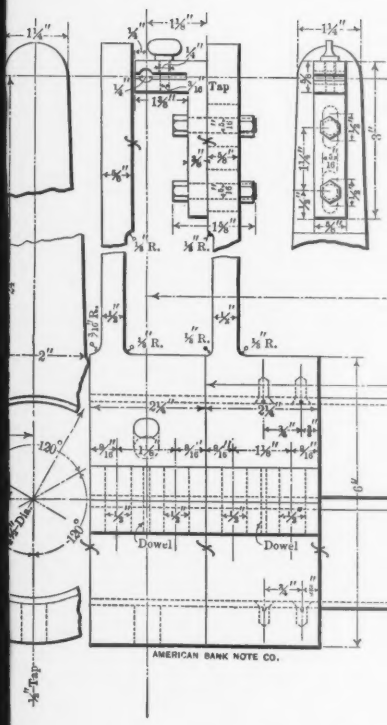
On the inside of the carriage there are four wheels 10″ diameter, 1″ thick, turning on small studs screwed into two castings which can be moved sideways and clamped to uprights of $6'' \times \frac{1}{2}''$ iron lag screwed to the carriage. These wheels prevent too much side motion being given to the weighing head. They are used only when pieces bend or twist out of shape. As the wheels are large compared with the pivots, there is but little error introduced, and generally they are not used until after the maximum has been passed and the piece has begun to fail.

THE TWISTING HOLDER.

The twisting holder is a heavy, triangular-shaped casting, having a hub on one side and a triangular-shaped recess running back about 8″ on the other side. At the three angles of this triangular opening are flattened bearing surfaces, on each of which rests a rectangular block grooved on the inner side to furnish a bearing for a toggle grip. The toggle grip is made of cast iron, with a toothed cast-steel plate about $\frac{1}{2}''$ thick at its acting face.



All Castings to be of Cast Iron.



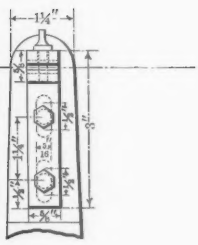
All Castings to be of

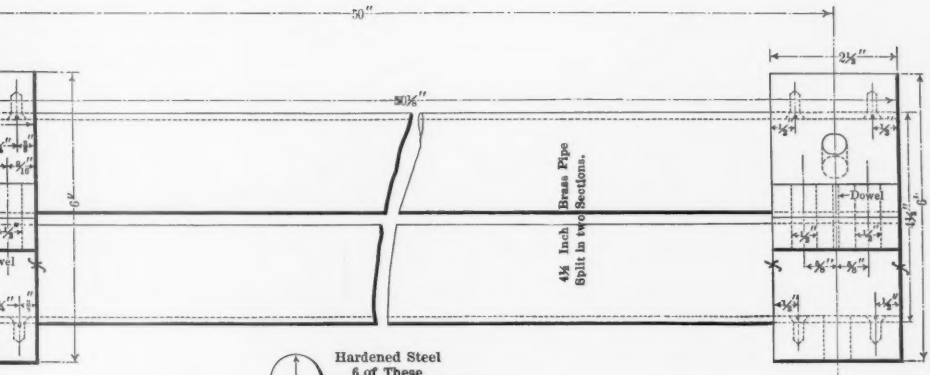
PLATE 1.

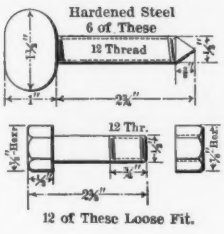
Design of Apparatus for Measuring Arc of Twist

Torsion Machine

1893. {E.F.M. / W.A.J.}

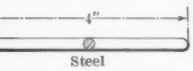






12 of These Loose Fit.

astings to be of Cast Iron.



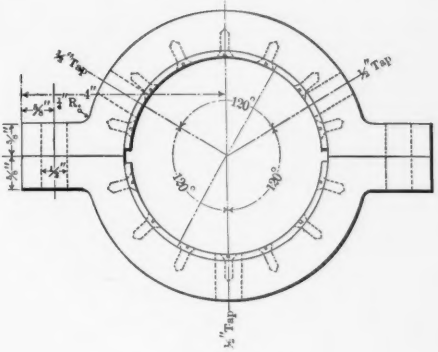
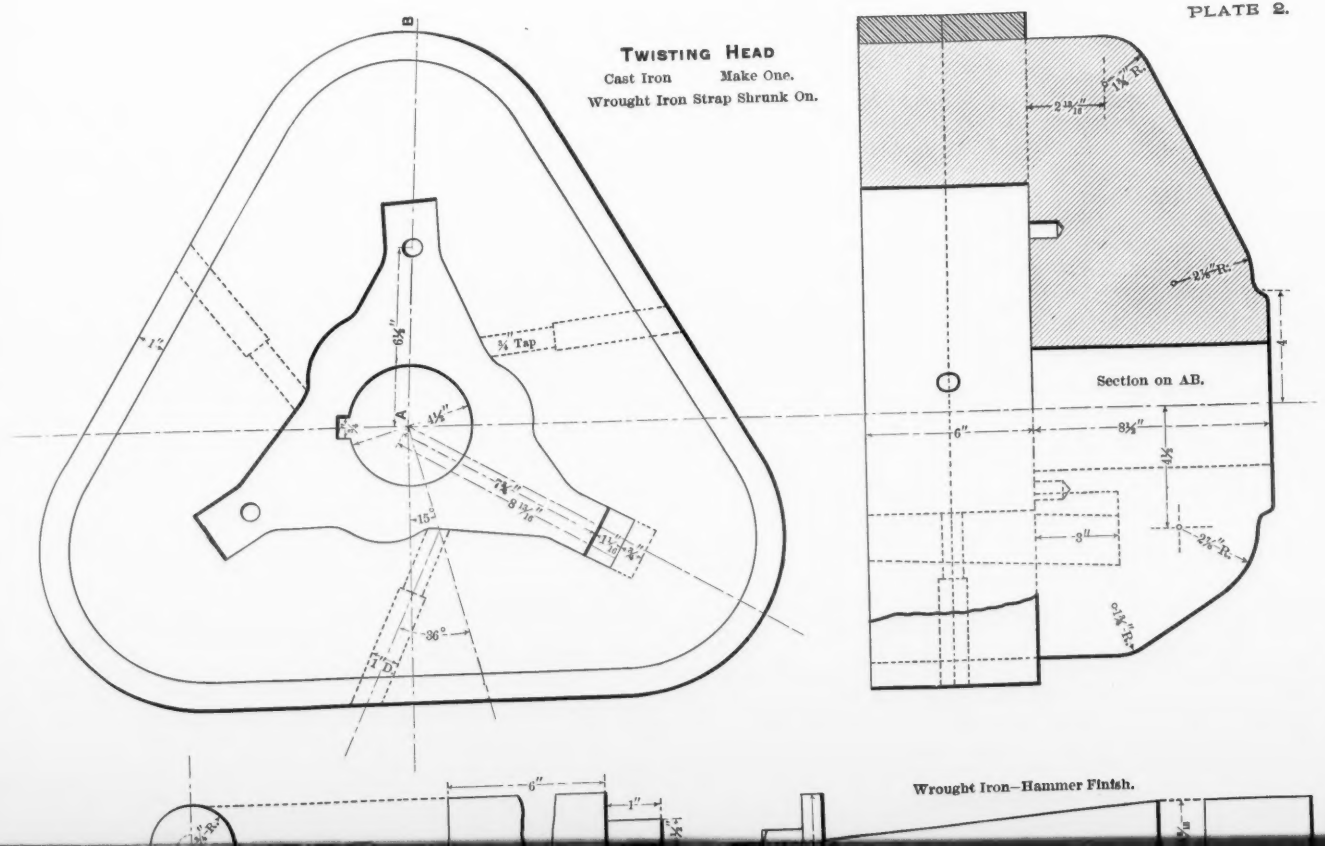
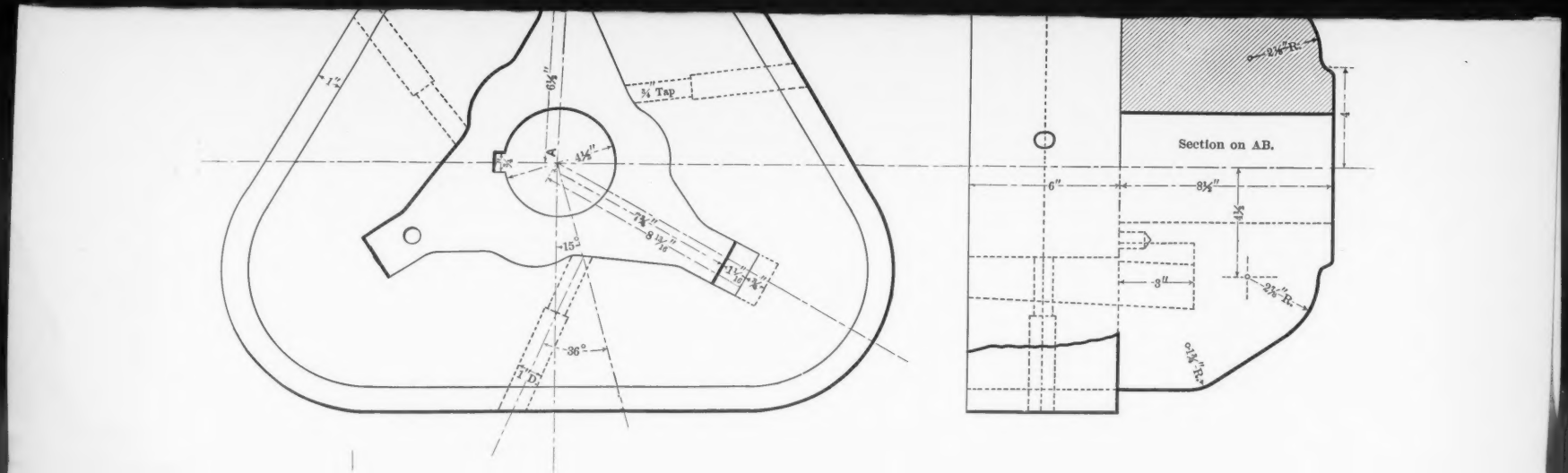


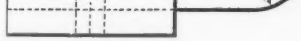
PLATE 2.

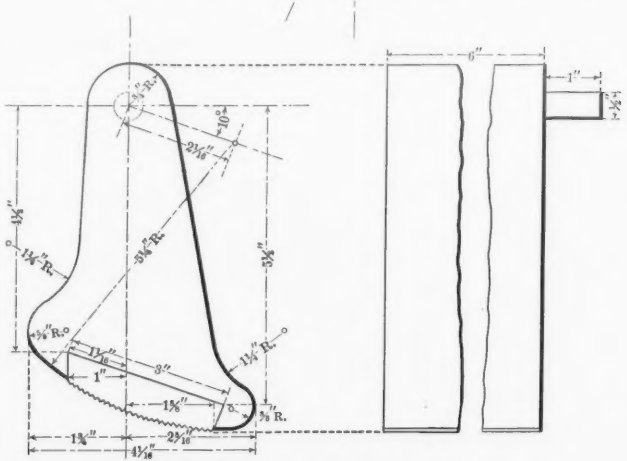
TWISTING HEAD

Cast Iron Make One.
Wrought Iron Strap Shrunk On.

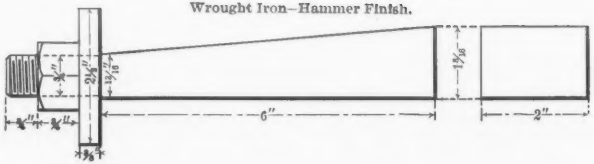


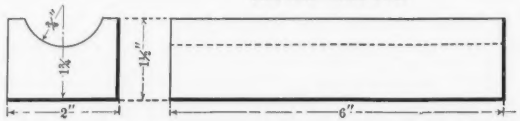

1"
6⅛"
¾" Tap
1½"
⅜"
A
B
1¾"
8 15/16"
15°
1 1/16"
¾"
36°
1" D.
2⅛" R.
Section on AB.
6"
8½"
4⅜"
3"
2⅛" R.
1¾" R.

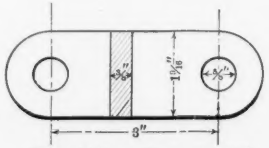




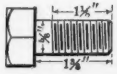
Cast Iron—Tool Steel Face—Make 8.



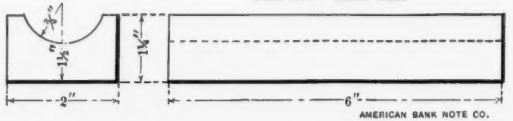




Wrought Iron—Hammer Finish.



Wrought Iron



AMERICAN BANK NOTE CO.

The acting face is an arc of a circle, the center from which the arc is struck being to one side of the bearing end of the grip. This enables one set of grips to take different sizes, and also prevents the toggle from straightening. This center is so taken that no matter what the size of specimen the angle of the toggle is nearly the same. It is evident that the greater the twist the harder the toggles grip.

For fear that in case a specimen should break off in the grips, the grips might fail to release, a steel wedge was placed in a recess in the holder casting under one of the bearing blocks. The wedge was made at about the angle of friction, and was kept from being pressed back by a nut and screw attached to it, the nut bearing on the casting. By unscrewing the nut and tapping the wedge back the jaws are loosened.

A number of specimens of 2″ diameter Norway iron have broken at the edge of the twisting holder, but in every case the jaws have released without the use of the wedge. For convenience in centering a specimen, three screws run through the casting and bear against the toggles.

On account of the enormous end pressure on the toggles, the holder casting was made heavy and was reinforced by two bands of 3″ x 1″ wrought iron shrunk on the outside. To better resist the strains the casting was made triangular-shaped. The holder in the weighing end is similar to the other, except that there is no hub, the triangular opening running way through the casting. Working drawings of some of the parts of the gripping holder are given in Plate 2.

MEASURING APPARATUS.

To find the shearing modulus of elasticity it is necessary to know the increase in the angle of twist for a certain increase in the twisting moment. The measuring apparatus made use of in finding the angle of twist is a slight modification of a style previously used in the laboratory. Drawings of it are shown in Plate 1. It consists of a piece of 4″ brass pipe about 54″ long, split longitudinally, and fastened together by means of bolts in castings at the ends.

At one end three pointed screws run through the casting and grip into the specimen. At the other end the brass pipe projects through a casting carrying an arm 24″ long, and rests in another similar casting fastened to the specimen by screws which go through elongated holes in the brass pipe. The pipe is free to turn in this last casting

and is also held up in place by it. One of these arms will turn with one part of the specimen, and the other arm with a part 50″ distant, 50″ being the distance between the set screws gripping into the specimen. The amount the two arms separate is measured by a micrometer carried by one of the arms. The chord thus measured is practically the same as the arc. Contact between the micrometer points is shown by a galvanometer.

Following is a sample log for recording readings and also results of some of the tests made by the fourth-year students on 2″ diameter bars of Norway and refined iron. The fractures show very plainly the quality of the iron. Some of the Norway bars twisted 16½ turns in a length of six feet. White stripes are painted on the bars before testing. A few of the fractured bars are shown in Figure 3.

TORSION MACHINE.

No. 8. November 6, 1893.

Specimen, Norway Iron.
Diameter, 2.02 inches. Length between jaws, 72 inches.
Distance from micrometer to center of test piece, 24.27 inches.
Distance apart on test piece of points between which arc of twist is measured, 50 inches.

Scale Reading.	Twisting Moment.	Micrometer Readings.				Mean.	Difference.	Remarks.
		1.	2.	3.	4.			
15	5,400	.3659	.3656	.3658	.3659	.3658	.....	Turned 16 times.
25	9,000	.1608	.1605	.1605	.1606	.1606	.2038	Stopped at 4.15, November 6, with a load on scale of 143 lbs.
35	12,600	—.0430	—.0430	—.0430	—.0430	—.0430	.2036	
35	12,600	.9297	.9295	.9294	.9296	.9296	.....	Broken November 7 at load of 208.25 on scale.
45	16,200	.6903	.6904	.6902	.6904	.6903	.2393	

Maximum load by scale . . . . . 208.25 pounds.
Maximum twisting moment . . . . . 74,970 inch-pounds.
Greatest outside fiber stress . . . . . 46,600 pounds.
Shearing modulus of elasticity (5400–9000) . . . . . 13,215,000.
Modulus of elasticity by tension test . . . . .

Signed.....

Kind of Iron.	Diameter in Inches.	Maximum Twisting Moment.	Maximum Outside Fiber Stress.	Shearing Modulus of Elasticity.	Number of Turns.	Distance between Grips.
Refined . .	2.03	84,240	51,285	12,471,000	4	72.1″
Refined . .	2.03	66,960	40,646	12,576,000	1.25	71.2″
Refined . .	2.03	70,200	41,743	11,372,000	3.5	70.5″
Refined . .	2.03	72,000	43,834	10,960,000	2.3	72.1″
Refined . .	2.03	61,920	36,820	11,393,000	2.8	71.8″
Refined . .	2 03	68,760	40,887	11,360,000	2.5	71.3″
Refined . .	2.03	78,120	46,453	12,871,000	2.8	69.3″
Norway . .	2.00	72,360	46,065	11,406,000	16.5	70.4″
Norway . .	2.02	74,970	46,600	13,215,000	16	72″
Norway . .	2.03	72,000	43,757	12,902,000	14	71.3″
Norway . .	2.02	74,520	46,321	12,247,000	17	70.4″
Norway . .	2.02	72,000	45,837	12,738,000	14.3	69.8″
Norway . .	2.03	74,880	45,692	11,361,000	15.5	70.3″

MATRICES WHICH REPRESENT VECTORS.

By W. H. METZLER, PH.D.

Received January 24, 1894.

SECTION I.

The matrix

$$\phi = \begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix}$$

may be considered as the quaternion

$$\frac{a_{11}(1-\lambda i)}{2} + \frac{a_{12}(j-\lambda k)}{2} + \frac{a_{21}(-j-\lambda k)}{2} + \frac{a_{22}(1+\lambda i)}{2}$$

or

$$\frac{a_{11}+a_{22}}{2} - \frac{\lambda(a_{11}-a_{22})}{2} i + \frac{(a_{12}-a_{21})}{2} j - \frac{\lambda(a_{12}+a_{21})}{2} k \text{ *}$$

where $\lambda = \sqrt{-1}$.

If the matrix ϕ is real, the quaternion will in general be imaginary. If, however, $a_{11} = a_{22}$ and $a_{12} + a_{21} = 0$, the quaternion will be real and reduce to $a_{11} + a_{12} j$. If a_{11}, a_{22} are conjugate imaginary of the form $a \pm \lambda b$, and a_{12}, a_{21} are conjugate imaginary of the form $\lambda c \pm d$, the quaternion will be real.

Let

$$\phi = \begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix} \quad \text{and} \quad \psi = \begin{pmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{pmatrix},$$

then

$$\phi\,\psi = \begin{pmatrix} a_{11}b_{11} + a_{12}b_{21} & a_{11}b_{12} + a_{12}b_{22} \\ a_{21}b_{11} + a_{22}b_{21} & a_{21}b_{12} + a_{22}b_{22} \end{pmatrix}$$

and it is easily seen that the product of the quaternions ϕ and ψ is the same as the product of the matrices ϕ and ψ considered as a quaternion.

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* *Vide* paper by Professor Cayley, Messenger of Mathematics, 14, 176.

The conjugate of the quaternion ϕ is

$$\frac{a_{11}+a_{22}}{2}+\frac{\lambda(a_{11}-a_{22})}{2}i-\frac{(a_{12}-a_{21})}{2}j+\frac{\lambda(a_{12}+a_{21})}{2}k,$$

which may be obtained from ϕ by changing the signs of a_{12}, a_{21}, and interchanging a_{11}, a_{22}, *i. e.*,

$$\mathrm{K}\,\phi=\begin{pmatrix} a_{22} & -a_{12} \\ -a_{21} & a_{11} \end{pmatrix}$$

The tensor of ϕ is given by

$$\begin{aligned}\mathrm{T}\,\phi&=\sqrt{\frac{(a_{11}+a_{22})^2}{4}+\frac{\lambda^2(a_{11}-a_{22})^2}{4}+\frac{(a_{12}-a_{21})^2}{4}+\frac{\lambda^2(a_{12}+a_{21})^2}{4}}\\&=\sqrt{a_{11}a_{22}-a_{12}a_{21}}\\&=\sqrt{g_1g_2}.\end{aligned}$$

If g_1, g_2 are the latent roots of ϕ, then $g_1+g_2=a_{11}+a_{22}$ and $\mathrm{S}\,\phi=\frac{a_{11}+a_{22}}{2}=\frac{g_1+g_2}{2}$. The matrix ϕ will represent a vector if $\mathrm{S}\,\phi=0$, and therefore $a_{11}=-a_{22}$. We may then write the vectors

$$\phi=\begin{pmatrix} a_{11} & a_{12} \\ a_{21} & -a_{11} \end{pmatrix}=\lambda a_{11}i+\frac{(a_{12}-a_{21})}{2}j-\frac{\lambda(a_{12}+a_{21})}{2}k$$

and

$$\psi=\begin{pmatrix} b_{11} & b_{12} \\ b_{21} & -b_{11} \end{pmatrix}=\lambda b_{11}i+\frac{(b_{12}-b_{21})}{2}j-\frac{\lambda(b_{12}+b_{21})}{2}k.$$

$$\begin{aligned}\text{The }\cos\hat{\phi\psi}&=\frac{-a_{11}b_{11}+\frac{(a_{12}-a_{21})(b_{12}-b_{21})}{4}-\frac{(a_{12}+a_{21})(b_{12}+b_{21})}{4}}{\mathrm{T}\,\phi\,.\,\mathrm{T}\,\psi}\\&=\frac{-2a_{11}b_{11}-a_{12}b_{21}-a_{21}b_{12}}{2\,\mathrm{T}\phi\,.\,\mathrm{T}\psi}.\end{aligned}$$

In order that ϕ and ψ are vectors at right angles to each other, we must have

$$2a_{11}b_{11}+a_{12}b_{21}+a_{21}b_{12}=0.$$

And since

$$\phi\psi=\begin{pmatrix} a_{11}b_{11}+a_{12}b_{21} & a_{11}b_{12}-a_{12}b_{11} \\ a_{21}b_{11}-a_{11}b_{21} & a_{21}b_{12}+a_{11}b_{11} \end{pmatrix},$$

we see that the condition that ϕ and ψ are vectors at right angles to

each other is the same as the condition that $\phi\,\psi$[1] is a vector, and it may be easily shown that $\chi = \phi\,\psi$ is a vector perpendicular to the plane of the vectors ϕ and ψ.

If ϕ is a unit vector, then

$$T\,\phi = -\,a_{11}^2 - a_{12}\,a_{21} = 1 = -\,\phi^2;$$

and if ϕ and ψ are unit vectors at right angles to each other, then $\phi\,\psi$ is a unit vector perpendicular to their plane.

If we take

$$\phi_1 = \begin{pmatrix} \sqrt{-1} & 0 \\ 0 & -\sqrt{-1} \end{pmatrix},$$

$$\phi_2 = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix},$$

$$\phi_3 = \begin{pmatrix} 0 & \sqrt{-1} \\ \sqrt{-1} & 0 \end{pmatrix},$$

then

$$\phi_1\,\phi_2 = -\,\phi_2\,\phi_1 = \phi_3,$$
$$\phi_2\,\phi_3 = -\,\phi_3\,\phi_2 = \phi_1,$$
$$\phi_3\,\phi_1 = -\,\phi_1\,\phi_3 = \phi_2,$$
$$\phi_1^2 = \phi_2^2 = \phi_3^2 = -\,1 \text{ and } \phi_1,\ \phi_2,\ \phi_3$$

will form a rectangular system of unit vectors, which are i, j, k, respectively.

Any matrix of the second order may be expressed in terms of these three and the matrix unity, so any quaternion may be expressed in terms of these three vectors and unity. We might, therefore, base the study of quaternions on that of matrices of the second order.

Matrices of any order may, in a similar way, be divided into a scalar and vector part. If ϕ is a matrix of order ω, then

$$S\,\phi = \frac{g_1 + g_2 + g_3 + \cdots + g_\omega}{\omega},$$

where $g_1, g_2, g_3 \ldots g_\omega$ are the latent roots of ϕ, and any matrix, the sum of whose latent roots equals zero represents a vector.

SECTION 2.

A matrix of the third order, considered as operating on a vector, gives a vector the components of which along the three axes are linear

[1] It is apparent that the condition that $\phi\,\psi$ is a vector is the same as the condition that $\psi\,\phi$ is a vector.

functions of the components of the original vector, and the matrix is called a linear vector function or operator.

Matrices having all their constituents zero except those along the principal diagonal are commutative in multiplication.

If we take

$$\phi = \begin{pmatrix} x & 0 & 0 \\ 0 & y & 0 \\ 0 & 0 & z \end{pmatrix} \text{ and } \rho = i + j + k,$$

then $\phi\rho = xi + yj + zk = \acute{\rho}$; that is, any vector whatever whose rectangular components have the lengths x, y, z, may be derived from ρ, whose rectangular components have the lengths 1, 1, 1, by operating on it by the matrix ϕ. From this we see that the study of vectors may be made to depend on that of such matrices as ϕ.

The treatment of vectors in this way is given in a paper by Dr. C. H. Chapman in the *American Journal of Mathematics*, Vol. XIII, No. 4. Through his paper Dr. Chapman speaks of the matrix ϕ, and the vector $\phi\rho = xi + yj + zk$ as the same; and the vector $\phi\psi$ is defined to be a new vector whose component lengths are the products of those of the factors, and consequently may be represented by the matrix $\phi\psi$. With this definition vectors are commutative, and on this ground the greatest claim is made by the author for this method of treatment.

It is to be observed that the symbol cy there introduced is the same as the symbol K employed by Dr. Taber in his paper *American Journal of Mathematics*, Vol. XII, No. 4, and is the extension of the quaternion (dual matrix) symbol K to matrices of the third order (nonions).

It strikes one on reading the paper that the advantages gained by this method, ingenious as it may be, are, on the whole, more than counterbalanced by its disadvantages.

THE EFFICIENCY OF JACK-SCREWS.

By EDWARD F. MILLER, S.B., and WILLIAM A. JOHNSTON, S.B.

Received February 26, 1894.

During the past four months quite a number of tests on jack-screws have been made in the Engineering Laboratories of the Massachusetts Institute of Technology. Some of these tests were made by the students as a part of the regular laboratory work, but the greater part were made by the writers. The tests were divided into three sets, three different kinds of oil being used to lubricate the jacks.

The results are interesting as showing how low the efficiencies are, and what increase in efficiency is obtained by using ball bearings between the head and cap or under the nut.

The test consisted in finding the pull at the end of a lever of known length necessary to lift a certain load on the jack. In all of the tests the pull given is the force necessary to start the jack, the pull after starting always being less.

$$\text{The efficiency} = \frac{\text{load} \times \text{pitch of screw in inches}}{3.1416 \times 2 \times \text{lever in inches} \times \text{pull}}.$$

Instead of using dead weights to load the jack, an apparatus consisting of I beams and levers was made, by means of which a load of 15,000 pounds could be obtained with 48 pounds on the weighing arm. The apparatus made is shown in Figure 1; although crude in appearance it is quite accurate. Two 8″ I beams fastened together are hung from two more I beams resting on wooden horses. These lower beams rest at one end on a knife edge *A* and at the other end on a knife edge *B* attached to the weighing beam. The jack is placed at *C*, one tenth the distance *AB* from *A*. The bottom of the jack bears on a plate which rests on the knife edge *C*. The lower I beams serve as a lever, giving a multiplication of 10 to 1. The weighing lever is a steelyard,

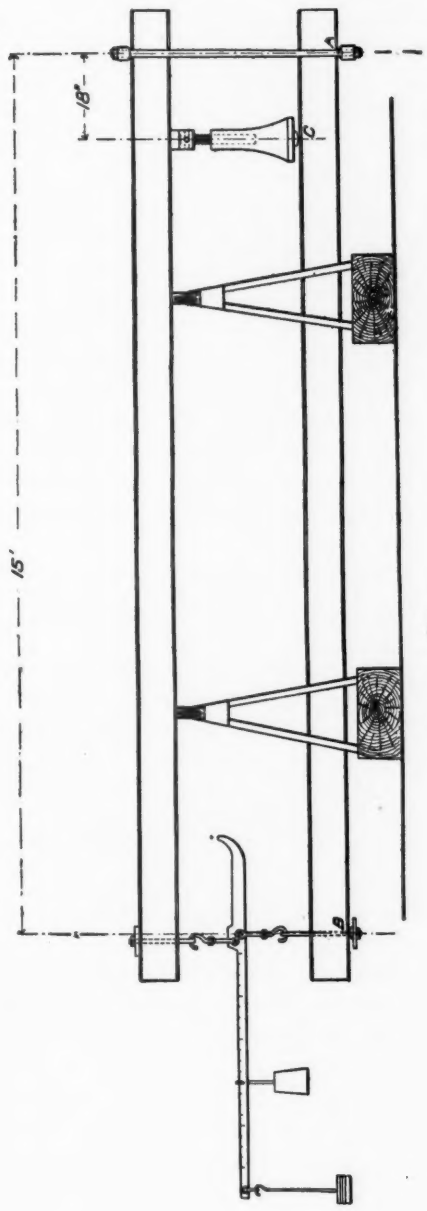

FIG. 1.

multiplying 31.25 to 1, so that the total multiplication of the two levers is 312.5. The weight of the jack and free end of the I beam lever is counterbalanced by weights placed in a scale pan hung from a knife edge at the end of the steelyard. The middle knife edge *C* is 8″ above the other two. This would cause an error if the lever had much motion, but as the extreme motion of the knife edge *B* is but $\frac{2}{10}$ of an inch there can be no appreciable error from this cause. The apparatus was tested, to see if the multiplication was correct, by resting a pair of platform scales on the knife edge *C* and applying a load of 2,000 pounds by means of a jack. The indication by the steelyard agreed with that shown by the scales.

In making a test the jack is screwed up until the steelyard is horizontal with the required load, then a steadily increasing pull is applied, through a spring balance, to the end of the lever until the lever moves. When the lever operating the jack moved in a vertical plane, an allowance was made for the weight of the lever, and this allowance added to the pull by the balance. The spring balances used in these tests were tested frequently with standard weights and corrections applied.

In the following tables the values given under the heading "average pull" are each the average of about five observations.

Jacks Nos. 1 and 5. Screw $2\frac{1}{4}$″ outside diameter cut with bastard thread $\frac{3}{10}$″ pitch. The annular ring at the head of the jack bearing against the cap is 3″ outside diameter, 1″ inside diameter.

Jacks Nos. 2 and 3. Screw 2″ outside diameter, $\frac{1}{4}$″ pitch square thread. Bearing ring at the cap is 3″ outside diameter, $1\frac{3}{4}$″ inside diameter.

Jack No. 4. Screw 2″ outside diameter, $\frac{1}{4}$″ pitch square thread. Cap is 3″ diameter, and bears all over.

Jack No. 6. Screw $2\frac{3}{8}$″ outside diameter, cut $\frac{1}{2}$″ pitch square thread. Bearing ring at cap 3″ outside diameter, $1\frac{1}{4}$″ inside diameter.

Jack No. 7. Screw $2\frac{7}{16}$″ outside diameter, $\frac{1}{4}$″ pitch square thread. The screw of this jack does not turn, but is forced upward by means of a nut bearing on the casting outside of the screw. This nut has ratchet teeth on its outer circumference, and is operated by a pawl and lever, the pawl being reversed to run the jack down. Between the nut and the casting there is a ball bearing. The cylindrical casting carrying the pawl protects the ball bearing from sand or dust.

Jacks Nos. 8, 9, 10 and *11.* The screws of these jacks are $1\frac{1}{2}$″ outside diameter and $\frac{1}{4}$″ pitch. The screw is somewhat peculiar, it

being cut flat on the bottom or bearing side and beveled to the base of the next thread on the upper side. The main casting or base to which the screw carries the load is turned cylindrical down to the foot, and serves as a guide for an outer cylindrical casting moved by the screw. This outer casting protects the parts from dust, and, as it takes all bending strains from the screw, renders the use of a screw of small diameter possible. Near the top of the outer casting there is a ratchet wheel, connected inside the casing with a bevel gear which in turn engages with another bevel gear fastened to the head of the screw. Between this bevel gear and the top of the outer casing there is a ball bearing. The ratchet is operated through the working lever by means of a double-ended pawl, which can be made to engage on either the up or the down stroke.

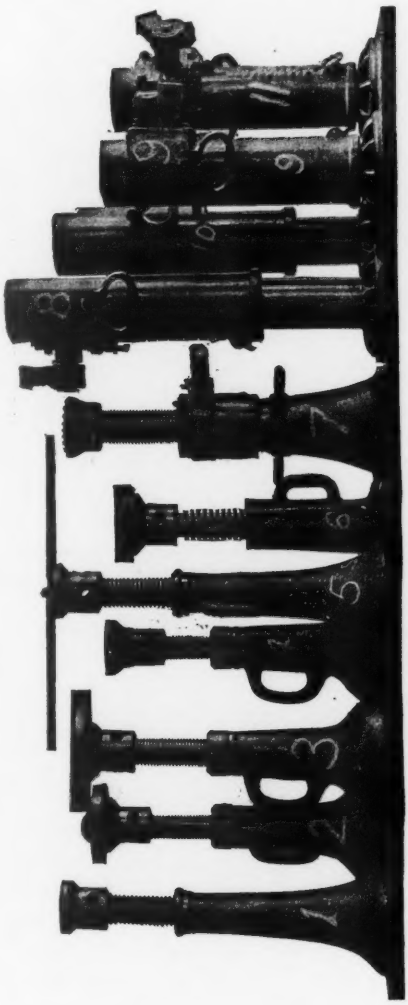

FIG. 2.

It will be seen by referring to the tables that the maximum variation from the average pull was greatest in the cases of Nos. 8, 9, and 11. This was probably due to inequalities in the teeth of the cast bevel wheels which turn the screw. In the case of Jack No. 10 the variation was so great that the results were not quoted.

JACK NUMBER 1.

Light Oil.						Cylinder Oil.						Tallow and Graphite.					
Loads.	Av. pull on lever. (Pounds.)	Maximum variation from average.	Length of lever. (Feet.)	Efficiency.	Average efficiency.	Loads.	Av. pull on lever. (Pounds.)	Maximum variation from average.	Length of lever. (Feet.)	Efficiency.	Average efficiency.	Loads.	Av. pull on lever. (Pounds.)	Maximum variation from average.	Length of lever. (Feet.)	Efficiency.	Average efficiency.
3,000	24.70	.6	3	16.8		3,000	25.45	.55	3	16.3		3,000	26.4	.2	3	15.7	
	24.30	.6	3	17.0	16.9		28.90	.90	3	14.4			24.1	.9	3	17.2	16.4
							28.30	.70	3	14.7	15.1						
5,000	41.40	.2	3	16.7		5,000	41.62	2.4	3	16.6		5,000	40.2	1.3	3	17.2	17.3
	41.20	.5	3	17.2	16.9		47.65	.85	3	14.5			39.9	.4	3	17.3	
							46.00	.75	3	15.0	15.4						
7,000	70	.2	6	16.8		7,000	58.45	1.6	3	16.5		7,000	55.5	.5	3	17.4	
	2.00	.3	6	17.3	17.0		30.10	.4	6	16.1			54.5	1.0	3	17.8	17.6
							30.10	.6	6	16.1	16.2						
9,000	37.75	.3	6	16.5		9,000	36.40	1.5	6	17.1		9,000	34.1	.2	6	18.2	
	38.55	.3	6	16.1	16.3		38.80	.7	6	16.0			34.5	.5	6	18.0	18.1
							37.85	1.2	6	16.4	16.5						
11,000	47.70	.2	6	15.9		11,000	46.35	1.2	6	16.4		11,000	41.5	.5	6	18.3	
	45.75	.3	6	16.6	16.2		46.00	.75	6	16.5			41.0	.5	6	18.5	18.4
							45.80	1.2	6	16.6	16.5						
13,000	54.90	.9	6	16.4		13,000	53.75	.75	6	16.7		13,000	49.9	.6	6	18.0	
	55.05	.5	6	16.3	16.4		54.90	.90	6	16.4			47.0	.5	6	19.1	18.6
							53.25	.75	6	16.9	16.7						
15,000	57.50	.5	7	15.7		15,000	57.10	2.1	7	15.6		15,000	56.5	.5	6	18.3	
	57.10	.5	7	15.6	15.7		59.90	.6	6	17.3			55.9	.9	6	18.5	18.4
							52.97	.7	7	16.8	16.6						

JACK NUMBER 2.

Light Oil.						Cylinder Oil.						Tallow and Graphite.					
Loads.	Av. pull on lever. (Pounds.)	Maximum variation from average.	Length of lever. (Feet.)	Efficiency.	Average efficiency.	Loads.	Av. pull on lever. (Pounds.)	Maximum variation from average.	Length of lever. (Feet.)	Efficiency.	Average efficiency.	Loads.	Av. pull on lever. (Pounds.)	Maximum variation from average.	Length of lever. (Feet.)	Efficiency.	Average efficiency.
1,000	8.38	.6	3	10.5													
	7.92	.4	3	14.0	12.2												
3,000	27.17	1.2	3	12.2		3,000	27.6	1.4	3	12.0		3,000	24.6	.6	3	13.5	....
	27.36	.8	3	12.1	12.2		26.4	1.6	3	12.6	12.3						
5,000	44.00	.5	3	12.6		5,000	47.6	1.4	3	11.6		5,000	43.8	1.2	3	12.6	...
	43.44	1.4	3	12.7	12.6		42.2	3.6	3	13.1	12 3						
7,000	31.32	.7	6	12.4		7,000	31.6	.4	6	12 2		7,000	57.0	1.0	3	13.6	....
	30.44	1.4	6	12.7	12.5		30.0	1.0	6	12.9	12.5						
9,000	41.60	.4	6	12.0		9,000	41.0	1.0	6	12.1		9,000	35.8	.8	6	13.8	....
	40.06	1.0	6	12.4	12.2		39.0	1.0	6	12.8	12.4						
11,000	50 83	1.7	6	12.0		11,000	47.4	.6	6	12.8		11,000	45.3	.8	6	13.4	....
	48.22	1.2	6	12.6	12.3		47.0	2.0	6	12.9	12.8						
13,000	50.75	.8	7	12.1		13,000	56.8	.8	6	12.6		13,000	52.2	.8	6	13.7	....
	50.32	1.3	7	12.2	12.2		55.2	.8	6	13.0	12.8						
15,000	58.42	.6	7	12.2		15,000	55.2	1.2	7	12.9		15,000	57.9	.6	6	14.3	....
	57.17	1.2	7	12.4	12.3		55.2	1.2	7	12.9	12.9						

JACK NUMBER 3.

Light Oil.						Cylinder Oil.						Tallow and Graphite.					
Loads. (Pounds.)	Av. pull on lever. (Pounds.)	Maximum variation from average. (Pounds.)	Length of lever. (Feet.)	Efficiency.	Average efficiency.	Loads.	Av. pull on lever. (Pounds.)	Maximum variation from average.	Length of lever. (Feet.)	Efficiency.	Average efficiency.	Loads.	Av. pull on lever. (Pounds.)	Maximum variation from average.	Length of lever. (Feet.)	Efficiency.	Average efficiency.
1,000	10.86	.9	3	11.1													
	11.50	.5	3	9.6	10.3												
3,000	36.21	1.2	3	10.0		3,000	31.1	2.9	3	10.7		3,000	31.3	1.3	3	10.6	....
	37 20	.8	3	8.9	9.5		30.2	1.7	3	11.0	10.8						
5,000	58.50	1.5	3	10.3		5,000	41.5	2.5	4	10.0		5,000	53.9	.9	3	10.3	....
	57.33	1.7	3	9.6	9.9		50.2	2.7	3	11.0	10.5						
7,000	39.62	1.6	6	9.8		7,000	41.0	2.0	5	11.6	11.6	7,000	39.4	.3	6	9.8	...
	39.17	2.9	6	9.9	9.9												
9,000	53.82	.8	6	9.2		9,000	44.4	3.6	6	11.2		9,000	49.6	.4	6	10.0	....
	50.62	2.6	6	9.8	9.5		42 7	1.3	6	11.6	11.4						
11,000	52.67	1.3	7	10.0		11,000	52.1	3.9	6	11.7	11.7	11,000	54.1	.4	6	10.1	....
	51.58	2.5	7	10.1	10.0												
13,000	....	....	....	....	....	13,000	52.4	3.6	7	11.8		13,000	....	....	....	....	....
							54.8	4.8	7	11.2	11.5						
15,000	....	....	....	....	....	15,000	....	....	....	....	....	15,000	....	....	....	....	....

JACK NUMBER 4.

Light Oil.						Cylinder Oil.						Tallow and Graphite.					
Loads.	Av. pull on lever. (Pounds.)	Maximum variation from average.	Length of lever. (Feet.)	Efficiency.	Average Efficiency.	Loads.	Av. pull on lever. (Pounds.)	Maximum variation from advance.	Length of lever. (Feet.)	Efficiency.	Average efficiency.	Loads.	Av. pull on lever. (Pounds.)	Maximum variation from average.	Length of lever. (Feet.)	Efficiency.	Average efficiency.
1,000	9.05	.3	3	12.2								3,000	24.8	.8	3	13.4	
	8.64	.9	3	12.8	12.5								22.8	.1	3	14.3	
													20.8	.2	3	16.8	14.8
3,000	27.00	1.0	3	12.3		3,000	22.4	.6	3	14.8							
	26.58	.6	3	12.4	12.4		28.2	1.8	3	11.8	13.3	5,000	40.4	.9	3	13 7	
													20.5	.1	6	13.5	
5,000	44.20	1.2	3	12.5		5,000	37.4	.6	3	14.8			22.1	.1	6	12.3	13.1
	44.22	.8	3	12.5	12.5		45.9	2.5	3	12.0	13.4						
												7,000	59.1	.6	3	13.1	
7,000	57.70	1.7	3	13.4		7,000	25.6	.6	6	15.0			30.2	.3	6	12.8	
	59.25	.7	3	13.1	13.2		31.8	2.7	6	12.2	13.6		29.5	.3	6	13.1	13.0
9,000	37.40	.6	6	13 3		9,000	32.4	.6	6	15.4		9,000	36.8	.8	6	13.5	
	36.40	1.5	6	13.7	13.5		41.5	1.5	6	12 0	13.7		30.5	.1	7	14.0	
													29.7	.5	7	14.3	13.9
11,000	46.40	1.4	6	13.1		11,000	39.2	2.8	6	15.5							
	45.50	.5	6	13.4	13.2		48.1	1.1	6	12.6	14.0	11,000	46.1	.4	6	12 7	
													26.3	.1	10	13.9	
13,000	54.50	.5	6	13.2		13,000	46.3	2.7	6	15.5			23.7	.2	10	15.4	14.0
	52.58	1.4	6	13·6	13.4		53.3	1.7	6	13.5	14.5						
												13,000	51.9	.4	6	13.9	
15,000	54.20	.8	7	13.1		15,000	48.2	1.2	7	14.7			29.0	.5	11	13.5	
	53.70	.7	7	13.2	13.1		48.2	3.2	7	14.7	14.7		25.7	.3	11	15.2	14.2
.....	.....	....	....	....	....	.....	.....	....	....	....	....	15,000	59.2	.8	6	14.0	
													30.4	.1	12	13.6	
													30.5	.1	12	13.6	13.7

JACK NUMBER 5.

Light Oil.						Cylinder Oil.						Tallow and Graphite.					
Loads.	Av. pull on lever. (Pounds.)	Maximum variation from average.	Length of lever. (Feet.)	Efficiency.	Average efficiency.	Loads.	Av. pull on lever. (Pounds.)	Maximum variation from average.	Length of lever. (Feet.)	Efficiency.	Average efficiency.	Loads.	Av. pull on lever. (Pounds.)	Maximum variation from average.	Length of lever. (Feet.)	Efficiency.	Average efficiency.
3,000	25.90	.9	3	16.0		3,000	29.00	1.0	3	14.3		3,000	23.0	.1	3	18 0	
	26.60	.6	3	15.6	15.8		26.95	.7	3	15.4			19.4	.3	3	21.4	19.7
							25.45	.3	3	16.3							
							25.05	.3	3	16.2							
							26.40	.6	3	15 7							
							26.60	1.4	3	15.6	15.6						
5,000	42.30	.7	3	16.3		5,000	43.65	1.7	3	15.8		5,000	18.8	.3	6	18 4	
	43.83	.4	3	15.8	16.0		41.10	.5	3	16.8			15.9	.2	6	21.7	20.0
							41.60	.4	3	16.6							
							39.60	.2	3	17.4							
							41.60	1.4	3	16.6							
							42.20	1.8	3	16.4	16.6						
7,000	29.70	.7	6	16.3		7,000	32.75	1.3	6	14.8		7,000	26.7	.3	6	18.1	
	30.65	.3	6	15.8	16.0		27.55	.6	6	17.6			23.0	.4	6	21.1	19.6
							56.75	.3	3	17.0							
							56.15	1.2	3	17.2							
							29.20	1.2	6	16.6							
							28.00	...	6	17.3	16.7						
9,000	41.60	.6	6	15.0		9,000	43.65	1.7	6	14.2		9,000	27.9	.2	7	19.1	
	41.60	.6	6	15.0	15.0		39.95	1.0	6	15.6			24 0	.5	7	22.2	20.6
							37.80	.4	6	16.4							
							35.80	.8	6	17.0							
							37.40	1.4	6	16.6							
							36.60	.6	6	17.0	16.1	....	....	....	....	....	....

JACK NUMBER 5. — *Concluded.*

Light Oil.						Cylinder Oil.						Tallow and Graphite.					
Loads.	Av. pull on lever. (Pounds.)	Maximum variation from advance.	Length of lever. (Feet.)	Efficiency.	Average efficiency.	Loads.	Av. pull on lever. (Pounds.)	Maximum variation from average.	Length of lever. (Feet.)	Efficiency.	Average efficiency.	Loads.	Av. pull on lever. (Pounds.)	Maximum variation from average.	Length of lever. (Feet.)	Efficiency.	Average efficiency.
11,000	49.4	.6	6	15.4		11,000	52.90	1.4	6	14.4		11,000	23 7	.2	10	19.2	
	49.3	.8	6	15.4	15.4		39.00	3.0	7	19.5			21.9	.2	10	20.8	
							46.50	.3	6	16.3							20.0
							44.75	1.5	6	17.0							
							45.40	.6	6	16.7							
							45.60	.6	6	16.7	16.8						
13,000	48.3	.7	7	15.9		13,000	50.90	2.4	7	15.1		13,000	26.2	.2	11	18.7	
	48.5	.5	7	15.9	15.9		45.50	1.3	7	16.9			22.9	.1	11	21.4	20.0
							47.45	.7	7	16.2							
							45.45	1.5	7	16.9							
							53.80	.8	6	16.7							
							54.20	1.8	6	16.6	16.4						
15,000	58.8	.3	7	15.1		15,000	56.80	2.8	7	15.6		15,000	28.5	.2	12	18.2	
	58.4	.6	7	15.2	15.2		56.35	3.7	7	15.8			28.6	.1	12	18.0	18.1
							53.25	1.3	7	16.7							
							51.90	.3	7	17.1							
							52.00	1.0	7	17.0							
							52.60	.6	7	16.9	16.5						

JACK NUMBER 6.

Cylinder Oil.						Tallow and Graphite.					
Loads.	Av. pull on lever. (Pounds.)	Maximum variation from average.	Length of lever. (Feet.)	Efficiency.	Average efficiency.	Loads.	Av. pull on lever. (Pounds.)	Maximum variation from average.	Length of lever. (Feet.)	Efficiency.	Average efficiency.
3,000	33.2	.3	3	20.0	....	3,000	21.6	.4	3	30.7	....
5,000	52.1	1.4	3	21.2	....	5,000	40.5	1.5	3	27.2	....
7,000	40.2	.3	6	19.2	....	7,000	31.5	1.0	6	24.6	....
9,000	50.6	2.1	6	19.6	....	9,000	41.4	.6	6	24.0	....
11,000	60.5	1.0	6	20.2	....	11,000	49.2	2.2	6	24.7	....
13,000	59.1	.6	7	20.8	....	13,000	60.9	.7	6	23.6	...
15,000	59.5	1.0	8	20.9	....	15,000	55.1	3.1	8	22.6	....
.....	....	....	....	....	....	17,000	61.1	3.1	8	23.0	....

JACK NUMBER 7.

CYLINDER OIL.

Loads.	Av. pull on lever. (Pounds.)	Maximum variation from average.	Length of lever. (Feet.)	Efficiency.	Average efficiency.	Loads.	Av. pull on lever. (Pounds.)	Maximum variation from average.	Length of lever. (Feet.)	Efficiency.	Average efficiency.
3,000	21.90	.9	2.75	16.5	....	7,000	24.20	.8	6	16.0	....
....	19.95	1.0	2.75	18.1	....	....	19.75	.6	6	19.6	....
....	20.95	1.5	2.75	17.3	....	....	23.35	4.8	6	16.6	....
....	18.70	1.5	2.75	19.3	....	....	19.70	.8	6	19.5	....
....	21.60	2.4	2.75	16.7	....	....	57.20	1.2	2.75	14.8	....
....	20.40	.6	2.75	17.7	....	....	47.80	1.2	2.75	17.7	....
....	21.50	1.5	2.75	16.8	....	....	56.35	2.1	2.75	15.0	....
....	21.00	2.0	2.75	17.2	....	....	53.85	1.2	2.75	16.7	....
....	22.80	1.2	2.75	15.9	....	....	58.40	2.4	2.75	14.5	....
....	22.40	1.6	2.75	16.1	....	....	48.00	1.0	2.75	17.6	....
....	21.10	.9	2.75	17.1	....	....	48.40	.6	2.75	17.4	....
....	26.65	2.7	2.75	13.6	....	....	25.10	2.1	6	15.4	....
....	22.05	2.0	2.75	16.4	....	....	22.55	1.5	6	16.7	....
....	21.50	.5	2.75	16.8	....	....	49.00	1.0	2.75	17.2	....
....	21.00	1.0	2.75	17.2	....	....	55.20	2.8	2.75	15.3	....
....	24.35	1.7	2.75	14.8	....	....	54.30	5.0	2.75	15.5	....
....	24.55	1.5	2.75	14.7	....	....	53.10	2.9	2.75	15.9	....
....	21.30	1.0	2.75	17.0	....	....	21.80	.8	6	17.8	....
....	20.60	.6	2.75	17.5	16.7	....	21.20	.3	6	18.2	16.7
5,000	39.05	1.0	2.75	15.4	....	9,000	31.10	1.0	6	16.0	....
....	35.00	1.5	2.75	17.2	....	....	28.35	.6	6	17.5	....
....	35.30	3.1	2.75	17.1	....	....	29.00	1.2	6	17.2	....
....	36.05	4.0	2.75	16.7	....	....	27.05	.3	6	18.4	....
....	41.00	2.0	2.75	14.7	....	....	32.80	1.2	6	15.2	....
....	34.80	2.8	2.75	17.3	....	....	29.40	1.6	6	16.9	....
....	40.70	4.2	2.75	14.8	....	....	31.05	3.0	6	14.9	....
....	39.35	1.8	2.75	15.3	....	....	28.70	2.3	6	17.3	....
....	41.60	1.4	2.75	14.5	....	....	34.80	1.8	6	14.3	....
....	35.10	.6	2.75	17.2	....	....	29.60	.6	6	16.8	....
....	34.30	.7	2.75	17.6	....	....	29.20	.7	6	17.0	....
....	43.60	3.6	2.75	13.8	....	....	31.65	2.4	6	15.7	....
....	36.60	1.6	2.75	16.5	....	....	29.35	1.7	6	16.9	....
....	35.20	.8	2.75	17.1	....	....	26.60	2.4	6	18.7	....
....	33.60	4.4	2.75	17.9	....	....	32.20	1.8	6	15.4	....
....	38.40	2.4	2.75	15.7	....	....	32.96	1.1	6	15.1	....
....	36.35	2.4	2.75	16.6	....	....	32.50	1.5	6	15.3	....
....	36.50	1.5	2.75	16.5	....	....	31.60	.6	6	15.7	....
....	32.50	.5	2.75	18.6	16.4	....	28.40	.6	6	17.5	16.4

JACK NUMBER 7.— *Continued.*

CYLINDER OIL.

Loads.	Av. pull on lever. (Pounds.)	Maximum variation from average.	Length of lever. (Feet.)	Efficiency.	Average efficiency.	Loads.	Av. pull on lever. (Pounds.)	Maximum variation from average.	Length of lever. (Feet.)	Efficiency.	Average efficiency.
11,000	39.50	1.5	6	15 4	....	15,000	53 60	1.4	6	15.5	....
....	33.90	.4	6	17 9	....	....	51.40	1.4	6	16 1	....
....	35.40	1.9	6	17.2	....	....	50.50	.8	6	16.4	....
....	34.15	.8	6	17.8	....	....	51.55	2 5	6	16.1	....
....	39.60	2.4	6	15.4	....	....	54.00	2.0	6	15.4	....
....	36.40	2.0	6	16 7	....	....	53.40	1.6	6	15.5	....
....	40.75	3.2	6	14.9	....	....	54.95	3.4	6	15.1	....
....	36.85	2.8	6	16.5	....	....	48.95	3.0	6	17.0	....
....	43.50	1.5	6	14 0	....	....	59 50	.5	6	13.9	....
....	38.40	1.0	6	15 8	....	....	59.00	1.0	6	14.0	....
....	38 90	.5	6	15 6	....	....	59.50	.5	6	13.9	....
....	37.10	4.3	6	16.4	....	....	56.10	1.4	7	12.7	....
....	35.00	2.5	6	17.4	....	....	56 25	3.0	7	12.6	....
....	36.20	.8	6	16 8	....	....	54.40	3.6	7	13.0	....
....	35.40	1 6	6	17.2	....	....	52.00	2.0	7	13.7	....
....	40.15	1.1	6	15 2	....	....	55.60	1.4	7	12 8	....
....	39.55	1.5	6	15.4	....	....	49.05	1.0	7	14.5	....
....	38.20	.8	6	15.9	....	....	54.60	1.4	7	13.0	....
....	33.30	.7	6	18.2	16.3	....	52.70	1.3	7	13 5	14.5
13,000	49.80	1.8	6	14.4	....	....	....	....	....	....	....
....	43.30	.8	6	16 6	....	....	....	....	....	....	....
....	45.50	1.7	6	15.8	....	....	....	....	....	....	....
....	44.20	2.2	6	16 3	....	....	....	....	....	....	....
....	44.20	1.8	6	16 3	....	....	....	....	....	....	....
....	43.20	.8	6	16.6	....	....	....	....	....	....	....
....	52.45	2.4	6	13.7	....	....	....	....	....	....	....
....	45.25	3.0	6	15.9	....	....	....	....	....	....	....
....	52.20	1.2	6	13.8	....	....	....	....	....	....	....
....	48 60	1.4	6	14.8	....	....	....	....	....	....	....
....	49.50	1.5	6	14 5	....	....	....	....	....	....	....
....	48 30	3.2	6	14 8	....	....	....	....	....	....	....
....	43 80	1.2	6	16 4	....	....	....	....	....	....	....
....	50.00	2 0	6	14.4	....	....	....	....	....	....	....
....	48.40	1 6	6	14 8	....	....	....	....	....	....	....
....	52.20	3.2	6	13 8	....	....	....	....	....	....	....
....	47.30	2.3	6	15 2	....	....	....	....	....	....	....
....	41.10	1.4	7	15.0	....	....	....	....	....	....	....
....	38.40	.6	7	16.0	15.3	....	....	....	....	....	....

JACK NUMBER 7. — *Concluded.*

Light Oil.						Tallow and Graphite.					
Loads.	Av. pull on lever. (Pounds.)	Maximum variation from average.	Length of lever. (Feet.)	Efficiency.	Average efficiency.	Loads.	Av. pull on lever. (Pounds.)	Maximum variation from average.	Length of lever. (Feet.)	Efficiency.	Average efficiency.
3,000	27.32	2.3	2.75	13.2		3,000	22.5	.8	2.75	16.1	....
	24.90	1.1	2.75	14.5							
	22.50	1.5	2.75	16.1	14.6						
5,000	47.40	2.4	2.75	12.7		5,000	35.9	2.7	2.75	16 8	....
	43.75	.8	2.75	13.8							
	33.94	1.0	2 75	17.8							
	34.17	1.6	2.75	17.6	15.5						
7,000	30.48	.8	6	12 7		7,000	55.7	4.8	2.75	15.2	....
	54.70	.7	2.75	15.4							
	49.00	1.0	2.75	17.2	15.1						
9,000	36.79	2.0	6	13.5		9,000	36.9	3.2	6.0	13.5	....
	32.90	1.1	6	15.1							
	31.17	1.9	6	16.0							
	31.14	.8	6	16.0	15.1						
11,000	44.27	2 5	6	13.7		11,000	42.9	1.6	6.0	14.2	....
	41.40	.6	6	14.7							
	37.10	.9	6	16.4							
	36.57	.4	6	16.6	15.3						
13,000	51.39	1.0	6	14.0		13,000	51.6	1.5	6.0	13.9	....
	50.60	.6	6	14.2							
	44.64	.6	6	16.1							
	43.37	.7	6	16.6	15.2						
15,000	57.33	1.6	6	14.5		15,000	47.3	.8	6.0	15.0	....
	48.50	1.5	7	14.7							
	51.14	.8	6	16.2							
	49.83	1.2	6	16.6	15.5						

JACK NUMBER 8.

Light Oil.						Tallow and Graphite.					
Loads.	Av. pull on lever. (Pounds.)	Maximum variation from average.	Length of lever. (Feet.)	Efficiency.	Average efficiency.	Loads.	Av. pull on lever. (Pounds.)	Maximum variation from average.	Length of lever. (Feet.)	Efficiency.	Average efficiency.
3,000	12.39	1.6	3	26 8		3,000	17.5	.2	3	18.9	....
	13.07	1.0	3	25.4	26.1						
5,000	22.70	1.8	3	24.3		5,000	25.5	.0	3	21.6	....
	21.40	1.0	3	25.8	25.0						
7,000	31.40	1.0	3	24.6		7,000	43.2	.3	3	17.9	....
	32.93	3.0	3	23.5	24.0						
9,000	24.55	1.5	6	20 3		9,000	47.8	1.3	3	20.8	....
	25.95	.4	6	19 2	19.8						
11,000	28.17	1 8	6	21 6		11,000	26.1	1.4	6	23.3	....
	28.33	1.7	6	21 5	21.6						
13,000	29.90	.5	6	24.0		13,000	29.1	.4	6	24.7	....
	30.90	1.1	6	23.3	23.8						
15,000	37.45	2.5	6	22.1		15,000	35.3	1.2	6	23.5	....
	35.12	2.4	6	23.6	22.9						

JACK NUMBER 9.

Light Oil.						Tallow and Graphite.					
Loads.	Av. pull on lever. (Pounds.)	Maximum variation from average.	Length of lever. (Feet.)	Efficiency.	Average efficiency.	Loads.	Av. pull on lever. (Pounds.)	Maximum variation from average.	Length of lever. (Feet.)	Efficiency.	Average efficiency.
3,000	13 9	1.0	3	23.9		3,000	12.7	.5	3	26.1	....
	17.0	1 0	3	19.6							
	16 0	1 0	3	20.7	21.4						
5,000	21.0	.5	3	25.6		5,000	24.0	1.0	3	23.1	....
	23.7	1.0	3	23.4							
	22.5	.5	3	24.6	24.4						
7,000	30.5	.5	3	25.4		7,000	40.5	2.0	3	19.1	....
	14.7	1.3	6	26.3							
	17.3	1.2	6	22.4	24.7						
9,000	42.4	1.4	3	23.5		9,000	47.1	2.4	3	21.1	....
	22 0	1.0	6	22.6							
	22.5	1.0	6	22.1	22.7						
11,000	23.8	.3	6	25.5		11,000	31.6	3.0	6	19.3	....
	24.6	.9	6	24.7							
	24.7	.7	6	24.6	24.9						
13,000	28.4	.4	6	25.3		13,000	38.5	3.0	6	18.7	....
	36.2	1 0	6	19.8							
	34.6	1.6	6	20.8	21.9						
15,000	46.0	2.0	6	18.0		15,000	42.1	5.0	6	19.7	....
	38.8	1.2	6	21.4							
	36 4	3.0	6	22 8	20.7						

JACK NUMBER 11.

Light Oil.						Tallow and Graphite.					
Loads.	Av. pull on lever. (Pounds.)	Maximum variation from average.	Length of lever. (Feet.)	Efficiency.	Average efficiency.	Loads.	Av. pull on lever. (Pounds.)	Maximum variation from average.	Length of lever. (Feet.)	Efficiency.	Average efficiency.
3,000	13.71	.4	3	24.2		3,000	21.6	1.6	3	15.4	....
	11.54	1.0	3	28.7	26.5						
5,000	23.11	2.0	3	23.9		5,000	30.1	1.4	3	18.4	....
	21.33	.3	3	25.9	24.9						
7,000	26.79	1.2	3	28.9		7,000	42.6	.9	3	18.2	....
	30.10	2.5	3	25.7	27.3						
9,000	17.40	1.2	6	28.6		9,000	47.5	4.	3	21.0	....
	18.00	1.0	6	27.6	28.1						
11,000	20.92	.9	6	29.0		11,000	28.8	.7	6	21.1	....
	19.90	1.4	6	30.6	29.8						
13,000	27.40	1.9	6	26.2		13,000	31.2	1.3	6	23.0	....
	27.80	.3	6	25.8	26.0						
15,000	29.00	1.0	6	28.6		15,000	36.1	1.4	6	23.0	....
	27.65	.7	6	30.0	29.3						

SUMMARY OF TESTS.

	Jack No. 1.			Jack No. 2.			Jack No. 3.		
Loads.	Light oil.	Cylinder oil.	Beef tallow and graphite.	Light oil.	Cylinder oil.	Beef tallow and graphite.	Light oil.	Cylinder oil.	Beef tallow and graphite.
3,000	16.9	15.1	16.4	12.2	12.3	13.5	9.5	10.8	10.6
5,000	16.9	15.4	17.3	12.6	12.3	12.6	9.9	10.5	10.3
7,000	17.0	16.2	17.6	12.5	12.5	13.6	9.9	11.6	9.8
9,000	16.3	16.5	18.1	12.2	12.4	13.8	9.5	11.4	10.0
11,000	15.2	16.5	18 4	12.3	12.8	13.4	10.0	11.7	10.1
13,000	16.4	16.7	18.6	12.2	12.8	13.7	....	11.5	....
15,000	15.7	16.6	18.4	12.3	12.9	14.3	....	....	....

	Jack No. 4.			Jack No. 5.			Jack No. 6.	
Loads.	Light oil.	Cylinder oil.	Beef tallow and graphite.	Light oil.	Cylinder oil.	Beef tallow and graphite.	Cylinder oil.	Beef tallow and graphite.
3,000	12.4	13.3	14.8	15.8	15.6	19.7	20.0	30.7
5,000	12.5	13.4	13.1	16.0	16.6	20.0	21.2	27.2
7,000	13.2	13.6	13.0	16.0	16.7	19.6	19.2	24.6
9,000	13.5	13.7	13.9	15.0	16.1	20.6	19.6	24.0
11,000	13.2	14.0	14.0	15.4	16.8	20.0	20.2	24.7
13,000	13.4	14.5	14.2	15.9	16.4	20.0	20.8	23.6
15,000	13.1	14.7	13.7	15.2	16.5	18.1	20.9	22.6

SUMMARY OF TESTS — *Concluded.*

	Jack No. 7.			Jack No. 8.		Jack No. 9.		Jack No. 11.	
Loads.	Light oil.	Cylinder oil.	Beef tallow and graphite.	Light oil.	Beef tallow and graphite.	Light oil.	Beef tallow and graphite.	Light oil.	Beef tallow and graphite.
3,000	14.6	16.7	16.1	26.1	18.9	21.4	26.1	26.5	15.4
5,000	15.5	16.4	16.8	25.0	21.6	24.4	23.1	24.9	18.4
7,000	15.1	16.7	15.2	24.0	17.9	24.7	19.1	27.3	18.2
9,000	15.1	16.4	13.5	19.8	20.8	22.7	21.1	28.1	21.0
11,000	15.3	16.3	14.2	21.6	23.3	24.9	19.3	29.8	21.1
13,000	15.2	15.3	13.9	23.8	24.7	21.9	18.7	26.0	23.0
15,000	15.5	14.5	15.0	22.9	23.5	20.7	19.7	29.3	23.0

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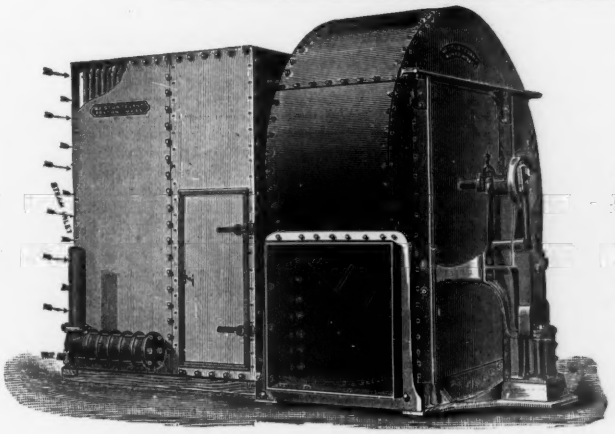

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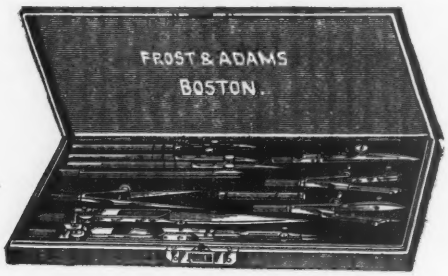

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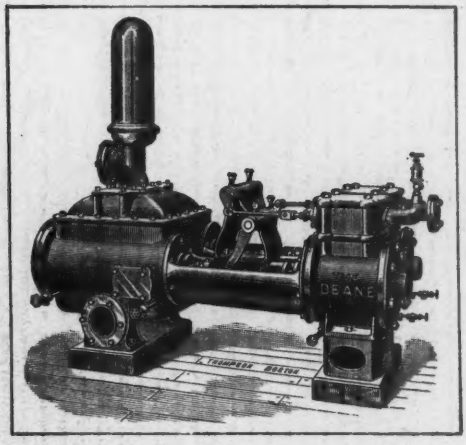

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